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STANDARD HANDBOOK

FOR

ELECTRICAL ENGINEERS

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Electrical Merchandising ▿ BusTransportation
Journal of Electricity and Western Industry
Industrial Engineer

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STANDARD HANDBOOK

FOR

ELECTRICAL ENGINEERS

PREPARED BY A
STAFF OF SPECIALISTS

FRANK F. FOWLE, S. B.
EDITOR-IN-CHIEF
CONSULTING ELECTRICAL ENGINEER, MEMBER AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS, ILLUMINATING ENGINEERING SOCIETY, WESTERN SOCIETY OF ENGINEERS AND NATIONAL ELECTRIC LIGHT ASSOCIATION

TOTAL ISSUE, SEVENTY-THREE THOUSAND

FIFTH EDITION
THOROUGHLY REVISED
SECOND IMPRESSION

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PREFACE TO THE FIFTH EDITION

During the period of seven years since the first appearance of the fourth edition of the STANDARD HANDBOOK there have been many new developments in the broad field of electrical engineering, stimulated in frequent instances by the necessities of the World War, the first year of which had nearly passed when the last edition came from the presses. The need for revision at this time, in order to maintain the standard character and authority of the Handbook, was self-evident, and therefore the Publishers called upon the staff who prepared the fourth edition to undertake the task. Several new Contributors were also invited to join in the undertaking.

In the preparation of the fifth edition the general arrangement and make-up of the fourth edition have been retained without change and the general policy outlined in the preface to that edition has also been the guiding policy in preparing the new edition. Every section in the fourth edition has been subjected to the scrutiny and criticism of the respective Contributors who originally prepared the text, with the few exceptions of those who in the meantime have passed on, or who for special reasons requested to be relieved. Each author was also furnished the comments or criticisms received from time to time from those who have had occasion to use the fourth edition in their own work.

Each section has been thoroughly revised by the substitution of up-to-date material and data for such as had become obsolete or of little practical value, and in some instances additional material has been added, although the size of the book imposed very definite limits in this direction. There have been substantial changes in every section with the exception of Sections 1, 23 and 25, which required only minor revision. In a few instances the sections have been rewritten in large part; this applies particularly to Sections 11, 14 and 17. New articles have also been added to Sections 15 and 22. By the permission

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of the A.I.E.E. the present "Standards of the A.I.E.E.," are given in Section 24, but are subject to the express stipulation which appears on the title page of the section.

As a whole the make-up and arrangement of the fourth edition seem to have met with the general approval of the large body of users of the Handbook, and many favorable comments have been received. In view, however, of certain suggestions relative to the enlargement of the index, special pains have been devoted to making it as comprehensive and complete as the space limitations will permit. It is hoped that the users of the fifth edition will find the new index ample in all respects.

The Editor is again glad to express appreciation and sincere thanks to the Contributors for their painstaking work and hearty coöperation in a task whose difficulties and trials are fully appreciated only by those who have been through them. The Publishers have, as heretofore, given the Editor full authority in all matters in his jurisdiction, from choice of contributors to selection of subject matter and make-up. They have also gone to great expense to make the book satisfactory in appearance and durability. Thanks are due to my assistant, Mr. V. H. Dupré, who has attended to many routine details of the editorial work and who has prepared the index.

FRANK F. FOWLE,
Editor-in-Chief.

CHICAGO, *June* 10, 1922.

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PREFACE TO THE FOURTH EDITION

The present edition of the STANDARD HANDBOOK for ELECTRICAL ENGINEERS, preparation of which was undertaken early in the year 1913 under the editorial direction of the writer, embodies so many changes and so much new matter that it is virtually a new book, retaining, however, the general features and scheme of arrangement which have received extensive endorsement in the prior editions. As heretofore, the STANDARD HANDBOOK is intended primarily as a reference book of practical information and data for practising engineers and a supplement to the standard text-books employed in teaching electrical engineering in colleges and universities. It is well recognized that limitations of space within a single volume of this character, even of the present size, render it impossible to treat each subject exhaustively. Our efforts have been concentrated chiefly on the task of presenting as much information and data of a practical nature as space would permit, reducing descriptive matter to the reasonable minimum and relying on references to standard works for extended dissertations on theory and highly special topics. Perhaps the most difficult task of all, in the present revision, was that of keeping the subject matter within the confines of a volume which would not be impossible in either the physical or the commercial sense.

Owing to the numerous advances in electrical science and the electrical arts since the appearance of the third edition in 1910, and owing also to certain criticisms which had been made concerning the earlier editions, the Publishers approved at the outset a broad and liberal editorial policy which greatly facilitated the work and minimized the burdens of a task that at best is a difficult one.

The first problem was the rearrangement of the sections for the purpose of securing a rational classification of major subjects and insuring a well-balanced presentation. A great deal of time was spent in consideration of this question before undertaking the details of the work. In the same manner much attention was given to the grouping of subjects under minor divisions in each main section, in order that the

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information on each subject might be presented in reasonably compact form, and at the same time be easily located.

Thus each numbered paragraph opens with a descriptive title or phrase in bold-faced type, while in other respects the use of such type has been limited to subheads and important key words which should catch the eye upon a casual glance over the pages. An entirely new feature is the consistent use of subheads throughout each section and the grouping of these on each section title page, for the double purpose of describing the contents in some detail and serving as a ready guide to any particular subdivision or minor subject. This general scheme of presentation is not intended to relieve the necessity for a thorough and complete index, but rather to supplement the latter and make the book of maximum usefulness. Another new feature is the addition of bibliographies at the end of each section or subsection, and the insertion of numerous references throughout the text to more extended or specialized literature.

In retaining the sectional or unit system of arranging a reference work of this character, both the Editor and the Publishers are convinced from past results that there is no other form of arrangement which is so well suited to the production of a useful and convenient handbook, or which makes possible the segregation of all the material relating to each subject, presented in logical sequence and so displayed as to give it the desired prominence.

Sections 1 to 5 inclusive cover the same general ground as in the third edition, but have been almost completely rewritten and considerably extended.

Sections 6 to 9 inclusive embrace the same subjects as Sections 6 to 8 in the third edition, but conform to a revised classification which is believed to be preferable to the former arrangement. These sections have also been entirely rewritten and substantially enlarged.

Section 10 covers the same general subject matter as the corresponding section in the last edition, but is entirely rewritten and greatly enlarged.

Sections 11 and 12 cover the same ground as Section 11 in the third edition, but are entirely new and much more comprehensive.

Section 13 replaces Section 18 in the old edition, being entirely

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rewritten; Section 14 replaces Section 12, with entirely new material; Section 15, Industrial Motor Applications, is a new section with entirely new subject matter.

Section 16 covers the ground of Section 13 in the third edition, and has been thoroughly revised. Section 17, Electric Vehicles, and Section 18, Electric Ship Propulsion, are both new sections.

Section 19 replaces Section 14 in the third edition, many portions of it being rewritten. Section 20 takes the place of old Section 9 with new material, and Section 21 replaces old Sections 15 and 16, also rewritten and altered somewhat in scope.

Section 22 takes the place of Section 17 in the old edition, with almost exclusively new material. Section 23, Mechanical Section, is a new section; Section 24 corresponds to Section 19 in the last edition; Section 25, General Engineering Economics and Central Station Economics, is entirely new. Section 20 in the former edition has been abandoned and its contents, or their revised equivalents, have been distributed among other sections.

The Editor takes this occasion to thank his numerous associates for their cooperation and enthusiasm throughout a long and difficult task, and to acknowledge the painstaking efforts of the Publishers concerning the mechanical features and their patience over the unexpected but seemingly unavoidable delays in completing the editorial portion of the work. Acknowledgment is also due to my assistant, Mr. J. C. Bogle, who has painstakingly performed a large share of the routine editorial work; to Mr. Walter Jackson, Associate Editor of the *Electric Railway Journal*, who has read the complete proofs before going to press; and to Mr. O. A. Kenyon, who has prepared the index.

FRANK F. FOWLE,
Editor-in-Chief.

CHICAGO, *June* 15, 1915.

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PREFACE TO THE THIRD EDITION

The preface to the first edition of the STANDARD HANDBOOK, which appears on another page, describes the "unit" system on which the work was developed. The present edition, the publishers believe, is somewhat of a triumph for this system. The thorough revision of a book of this size, when manufactured according to the usual plan, is commercially impossible except at long intervals when the changes in the art become so great as to demand an entirely new book. The "unit" system employed in the STANDARD HANDBOOK permits thorough revision in part or as a whole without any of the usual limitations.

In the present revision the authors of the various sections were allowed a free hand in so far as mechanical details were concerned. They were not restricted in space or compelled to cut and prune material to fit pages. The result is a book that has been thoroughly revised from cover to cover so that it could be fairly called a new STANDARD HANDBOOK.

The following synopsis gives a brief outline of the changes and additions that have been made to the various sections.

Section 1, Units, is corrected and slightly enlarged.

Section 2, Electric, Magnetic and Dielectric Circuits, is greatly enlarged. The general theory of electric and magnetic circuits is entirely rewritten and the calculation of inductance and capacity is given in greater detail than before.

Section 3, Measurements and Measuring Instruments, is greatly enlarged. Several new instruments are described, tests of self and mutual inductance have been added and a section devoted to pyrometers and high temperature measurements has been included. The design of rheostats and motor starters has been transferred to Section 5.

Section 4, Properties of Conductor, Resistor and Insulating Materials, is enlarged more than any other section. Many tables have been added giving data on the latest types of conductors and cables. An entirely new section giving the properties of a large number of commercial resistor alloys has also been added and the magnetic testing of iron has been entirely rewritten and now forms a very comprehensive treatment of the latest practice in this important subject.

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Section 5, Magnets, Resistors, Condensers and Reactors, has been enlarged in scope to include resistors, condensers and reactors. In the sections on magnets, a discussion of the energy relations in a plunger magnet has been added. The section on resistors contains the design of rheostats, formerly in Section 3. To this section have been added the design of induction motor starters, the heating of wires, cables and embedded conductors, the calculation of fuses and tables for use in heating calculations. A new skin effect for various metals has also been added. In the condenser and reactor sections, the electrical calculations are given, and considerable space is devoted to the electrolytic condenser. Almost all of the material in this section is entirely new.

Section 6, Transformers and Converters, is thoroughly revised and considerably enlarged. The use of silicon steel has revolutionized transformer design and hence this section has been completely overhauled. As the book goes to press it is the only available up-to-date treatment of transformers. In the converter section numerous additions are made, the most important being a discussion of the split-pole converter.

Section 7, Generators, has been corrected and slightly revised.

Section 8, Motors, has been revised, discussions of new motors being added to the alternating current commutating motor section. New design data are given for both a.c. and d.c. motors.

Section 9, Batteries, has been corrected and revised, with slight additions.

Section 10, Central Stations, has been thoroughly revised and largely rewritten. The scope is the same. Many cost data have been added.

Section 11, Transmission and Distribution, excepting the underground construction and mechanical transmission, has been entirely rewritten. It is believed now to be thoroughly abreast of the times in the calculation and construction of transmission and distribution systems. Many tables have been calculated especially for this section. Practically all of the old tables have been discarded. Inductive reactance and charging current for all sizes of wire and cable and all spacings are given for 25 and 60 cycles. Tables giving the stresses in wires and cables of various sizes for wind, and wind and sleet conditions are also among the additions.

Section 12, Illumination, has been corrected and revised.

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Section 13, Traction, has been corrected, revised and enlarged. The locomotive section has been entirely rewritten, and more space has been given to the method of constructing speed-time curves.

Section 14, Electrochemistry, has been thoroughly revised and somewhat enlarged.

Section 15, Telephony, has been entirely rewritten. It is now a comprehensive treatise and represents a new method of presenting the subject.

Section 16, Telegraphy, is corrected.

Section 17, Miscellaneous Applications of Electricity, is corrected and somewhat enlarged.

Section 18, Wiring, is corrected and brought to date.

Section 19, Standards, is considerably enlarged. The latest changes in the A. I. E. E. Standardization Rules have been noted, and standard specifications for rubber insulation, copper conductors and transformers have been added.

Section 20, Tables and Statistics, has been corrected and enlarged by adding telephone, telegraph and central station statistics and by general revision.

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PREFACE TO THE FIRST EDITION

In the preparation of the STANDARD HANDBOOK the publishers have adapted the "unit" system to bookmaking. The entire field of electrical engineering was divided into twenty sections or units, each complete in itself. These twenty sections were arranged in what seemed to be a logical order and each was assigned to a specialist. Each author was supplied with a detailed outline of all the sections, thus avoiding repetitions and duplication of material as far as desirable. All of the material thus brought together was carefully edited to obtain uniformity of style, symbols, abbreviations, units, etc., and to connect the various parts by cross-references.

Some repetitions are purposely made to save the time of the user. For instance, transformer oil is treated under Insulating Materials in Section 4, but a brief outline of its important qualities is again given in Section 6 under Transformers, with a cross-reference to guide the reader to the fuller treatment in Section 4.

The Index embodies some new features. All references are made to section and paragraph. In each section the paragraphs are numbered from one to the end, and the section and paragraph numbers are set at the head of the page; the page number appearing in an inconspicuous place at the foot, for the guidance of the printer only. Cross-references are always made through the index to avoid errors and to guide the user to *all* other parts of the book where that subject may be treated.

The studied use of bold-face type is also intended to save time by bringing out in a prominent way the real subject of each paragraph.

Recognized standards have been followed wherever possible. Those recommended by the national societies or organizations have usually been followed. Section 19 is entirely given up to Standardization Rules and Reports, including the full report of the American Institute of Electrical Engineers of June, 1907, and that of the American Street and Interurban Railway Engineering Association, ratified in October, 1907.

The publishers cannot hope for absolute accuracy in this

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first edition of a work containing such a mass of figures and data, although the greatest care has been exercised in its preparation. Any suggestions, criticisms, or corrections from users will be of great service in making THE STANDARD HANDBOOK a standard in fact as well as in name.

December 12, 1907.

PREFACE TO THE SECOND EDITION

No new material has been added to this edition of the STANDARD HANDBOOK, with the exception of directions for resuscitation from electric shock, which have been inserted at the end of the book. However, every page has been most carefully read and every possible effort made to insure the accuracy of all data and perfection of the typographical work. Several of the tables, which were especially prepared for this book, have been recalculated and others have been checked by plotting the values and recalculating those which did not fall on a smooth curve.

The success of the STANDARD HANDBOOK has been phenomenal. The general interest in the work has been manifested by the many letters received from prominent men commending its general character and offering suggestions and criticisms. It has already been adopted for use as a text-book in thirty universities and colleges.

The publishers take this occasion to express their appreciation of its reception by the profession, and to thank those who by their kindness in pointing out typographical and other errors, have materially assisted in the work of correction.

NEW YORK, *May*, 1908.

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SECTIONS AND AUTHORS

SECTION 1

UNITS, CONVERSION FACTORS AND TABLES. By Arthur E. Kennelly, A.M., Sc.D.

Systems of Units, Historical Sketch, Evolution of Practical Electromagnetic System of Units, Definitions, Dimensional Formulas, Weights and Measures, Conversion Tables and Mathematical Constants and Tables.

SECTION 2

ELECTRIC AND MAGNETIC CIRCUITS. By Vladimir Karapetoff

Electric Potential, Electric Currents, Continuous-current Circuits, Electromagnetic Induction, The Magnetic Circuit, Inductance, Hysteresis, Eddy Currents, The Dielectric Circuit, Transient Currents, Alternating-current Circuits, Complex Waves, Polyphase Systems and Transmission Circuits.

SECTION 3

MEASUREMENTS AND MEASURING APPARATUS. By F. Malcolm Farmer; George K. Burgess, Sc.D.; Paul D. Foote, A.M.; Reginald J. S. Pigott and William J. Drisko, S.B.

Galvanometers, E.M.F. and Current Measurements, Resistance Measurements, Power and Energy Measurements, Curve-drawing Instruments; Measurements of Inductance, Capacity, Wave-form, Frequency, Slip, Torque and Speed; Magnetic Measurements, Thermometry, Pyrometry, Heat Conductivity, Fuel and Gas Analysis; Water, Gas, Air and Steam Meters; Precision of Measurements.

SECTION 4

PROPERTIES OF MATERIALS. By Frank F. Fowle, S.B.

Conductor Materials, Wire Gages, Wire Tables, Copper, Aluminum, Copper-clad Steel, Iron and Steel, Bronze, Miscellaneous Metals, Resistor Materials, Carbon and Graphite, Skin Effect; Magnetic Materials, Composition and Properties, Core Losses, Sheet Gages, Commercial Sheets, Magnet Steel; Insulating Materials, Classification, Discussion of Properties, Solid Natural Materials, Vitrified Materials, Fibrous Materials, Molded Compositions, Rubber and Its Derivatives, Varnishes and Compounds, Insulating Oils, Gases; Structural Materials, Cast Iron, Wrought Iron, Steel, Annealing, Hardening, Tempering, Steel Wire and Cable, Non-Ferrous Metals, Concrete, Brick, Stone, Timber, Belting and Rope, Properties of the Elements, Atomic Weights, Densities, Specific Heats, Properties of Water and Air.

SECTION 5

MAGNETS, INDUCTION COILS, CONDENSERS AND RESISTORS. By Charles R. Underhill and Leonard Kebler

Permanent Magnets, Electromagnets, General Theory, Tractive Electromagnets, Conditions for Maximum Work, Standard Electromagnets, Portative Electromagnets, Polyphase Electromagnets, Heating, Magnet Wires, Calculations, Construction, Testing; Induction Coils, Types, Windings, Interrupters; Condensers, Types, Plate Condensers, Electrolytic Condensers; Resistors, Field Rheostats, Speed-regulating Rheostats, Dimmers, Starting Rheostats, Battery-charging Rheostats and Resistance Units.

SECTION 6

TRANSFORMERS AND RECTIFIERS. By Charles Le G. Fortescue

Theory, Design, Insulation, Cooling, Coil Grouping, Transformers for Power Service and Distribution Systems, Multiple Operation, Polyphase Transformations, Constant-current Transformers, Auto-transformers, Instrument Transformers, Miscellaneous Applications, Testing, Installation, Care and Operation; Potential and Current Regulators, Reactors and Rectifiers.

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SECTION 7

ALTERNATING-CURRENT GENERATORS AND MOTORS By Comfort A. Adams and Henry M. Hobart

Synchronous Machines, Armature Winding, E.M.F. Generation, Th Magnetic Circuit, Characteristics of Synchronous Alternators, Synchronou Motors, Parallel Operation, Design, Insulation, Efficiency, Ventilation, Con struction and Testing; Induction Machines, Theory of Polyphase Motors Characteristics, Magnetizing Current, Leakage Reactance, Circle Diagram Efficiency, Standard Polyphase Motors, Induction Generators, Design Single-phase Motors and Their Speed Control; Commutator Motors, Auxil iary Commutating Machines, Phase Modifiers, Motor-generators an Frequency Changers.

SECTION 8

DIRECT-CURRENT GENERATORS AND MOTORS. By Alexande Gray, B.Sc., Whit. Sch.

Types, Windings, Armature Reactions, Commutation, Armature Design Field Design, Construction, Insulation, Cooling, Efficiency, Characteristics Regulation, Weights, Costs, Standard Machines, Thury System, Motor generator Sets, Operation and Testing.

SECTION 9

CONVERTERS AND DOUBLE-CURRENT GENERATORS. By F. D Newbury, M.E. and Alexander Gray, B.Sc., Whit. Sch.

Synchronous Converters, Theory, Design, Characteristics, Applications Operation, Testing; Inverted Converters, Motor Converters, Direct-curren Converters, Dynamotors and Double-current Generators.

SECTION 10

POWER PLANTS. By Reginald J. S. Pigott, Arthur T. Safford an George I. Rhodes

Steam Power Plants, Laws of Heat Transfer, Boilers, Furnaces, Stokers Chimneys, Mechanical Draft, Fuel, Water Supply, Coal and Ash Handling Engines, Turbines, Condensers, Heaters, Economizers, Pumps, Piping an Testing; Gas Power Plants, Producers, Superheaters, Condensers, Scrubbers Purifiers, Holders, Properties of Gas, Engines, Piping and Testing; Oil Powe Plants, Engines, Testing; Hydraulic Power Plants, Hydraulics, Flow For mulas, Stream Flow, Dams, Headworks, Water Wheels and Testing; Build ings and Foundations; Electrical Equipment, Generators, Excitation Voltage Control, Switching, Station Transformers, Lightning Arresters an Wiring; Power-plant Economics.

SECTION 11

POWER TRANSMISSION. By Harry E. Clifford, S.B. and Chester L. Dawes, S.B.

Transmission Systems, Electrical Calculations, Tables of Reactance and Charging Current, Design, Corona, Insulators, System Connections, Switch ing, Spans and Supports, Construction, Cables, Substations, Operation Economics and Cost Data.

SECTION 12

DISTRIBUTION SYSTEMS. By Harry Barnes Gear, A.B., M.E.

Classification, Applications, Types of Circuits, Circuit Design, Substations Regulation, Secondary Distribution, Transformation, Protection, Construc tion and Economics.

SECTION 13

INTERIOR WIRING. By Terrell Croft

Fire Risk, Methods of Wiring, Wires and Cables, Fittings and Accessories, Calculations, Lay-outs, Installation, Protection and Miscellaneous.

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SECTION 14

ILLUMINATION. By Preston S. Millar

Production of Light, Incandescent Lamps, Carbon Filament, Metallised Carbon Filament, Tantalum, Tungsten, Gas-filled Type; Arc Lamp Characteristics, Carbon-electrode, Flame Arc, Metallic Electrode, Tube Lamps, Lighting Accessories, Reflectors, Indirect and Semi-indirect Lighting; Illumination Calculations, Flux, Candle-power, Intensity, Brightness, Efficiency; Applied Illumination, Fundamentals of Vision, Characteristics of Illumination, Physiological and Psychological Effects, Methods, Design, Costs; Photometry, Fundamentals, Standards, Apparatus, Spectrophotometers, Colorimeters and Testing.

SECTION 15

INDUSTRIAL MOTOR APPLICATIONS. By the following specialists:

Leon P. Alford	Chester W. Drake	Arthur C. Eastwood
Wilfred Sykes	David L. Lindquist	Fred J. Postel
Joseph H. Brown	Merton S. Leonard	C. D. Gilpin
H. McL. Harding	Graham Bright	Augustus C. Smith
William W. Crosby	Joseph H. Wallace	Geo. B. Massey
C. W. Pendell	Charles E. Carpenter	A. E. Hall
Wirt S. Scott	Frits Balzer	Bernard Lester
Clark T. Henderson	Arthur Simon	

Machine Tools, Wood-working Machinery, Traveling Cranes, Electric Hoists, Elevators, Power Pumps, Air Compressors, Fans and Blowers, Coal and Ore Handling Machinery, Telpherage Systems, Steel Mills, Cement Mills, Coal Mining, Refrigerating Plants, Textile Mills, Paper and Pulp Mills, Printing, Binding and Linotype Machinery, Flour Mills, Beet-sugar Mills, Laundry Machinery, Small-motor Applications and Motor Control.

SECTION 16

ELECTRIC RAILWAYS. By Albert H. Armstrong, E. E. Kimball, Norman W. Storer, Robert D. McManigal, Axel Ames, Albert F. Ganz and Albert S. Richey

Electric Traction, Train Resistance, Speed-time Curves, Motor Characteristics, Energy and Power Consumption, Motor Control, Types of Motors, Braking, Trucks and Car Bodies, Self-propelled Cars, Locomotives, Distribution, Substations, Railway Signalling, Types of Fixed Signals, Trolley-operated Systems, Track Circuits, Interlocking, Block System; Electrolysis, Surveys, Means of Prevention, Electrolysis in Concrete, Municipal and State Regulations.

SECTION 17

ELECTRIC VEHICLES. By John G. Carroll

Classification, Passenger Cars, Commercial Trucks and Tractors, Industrial Trucks and Tractors, Vehicle Motors, Control; Batteries, Charging, Charging Equipment.

SECTION 18

ELECTRIC SHIP PROPULSION. By Henry M. Hobart

Ship Resistance, Propeller Characteristics, Systems of Propeller Drive, Types of Vessel For Different Service, Electric Propulsion and Examples of Electrically Propelled Ships.

SECTION 19

ELECTROCHEMISTRY. By E. F. Roeber, Ph.D. and J. W. Richards, Ph.D.

Interpretation of Chemical Equations, Laws of Gases, Laws of Solutions, Energy Relations, Electric Furnaces and Their Products, Electrolytic Processes and Reactions, Industrial Electrolytic Processes, Electroplating, Refining of Metals; Electrolysis of Water, Alkaline Chlorides, Copper, Nickel, Zinc, Aluminum, Sodium, Magnesium and Calcium; Discharges through Gases, Fixation of Atmospheric Nitrogen, Electromagnetic and Electrostatic Processes.

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SECTION 20

BATTERIES. By Walter E. Winship, Ph.D.

Primary Batteries, Wet Cells, Dry Cells; Storage Batteries; Lead Storage Batteries, Electrolyte, Testing, Stationary Batteries, Vehicle Batteries, Train-lighting Batteries, Miscellaneous Applications, Battery Rooms, Regulating Equipment, Operation, Depreciation and Maintenance; Alkaline Storage Batteries.

SECTION 21

TELEPHONY, TELEGRAPHY AND RADIOTELEGRAPHY. By Frank F. Fowle, S.B., and Louis W. Austin, Ph.D.

Telephone Instruments, Switchboards, Intercommunicating Systems, Phantom Circuits, Manual Telegraph Systems, Simplex and Composite Sets, Dispatching and Patrol Systems, Fire and Police Alarm Systems, Cable, Protectors, Cross-talk and Inductive Disturbances, Transmission, Construction, Testing; Radiotelegraphy, High Frequency Oscillations, Antennæ, Exciting the Antenna, Undamped Oscillations, Transmission of Waves, Receiving Circuits, Detectors, Continuous Oscillations, Atmospheric Disturbances, Measurements.

SECTION 22

MISCELLANEOUS APPLICATIONS OF ELECTRICITY. By the following specialists:

E. N. Lightfoot	Otis Allen Kenyon	John C. Bogle
Harry B. Gear	H. A. Hornor	Major Edw. D. Ardery
John E. Newman	Frank F. Fowle	Milton W. Franklin
Edwin P. Adams	Eugene W. Caldwell	J. S. Shearer
Ernest J. Berg	Elmer A. Sperry	F. A. Annett

Resuscitation, Electric Heating and Cooking, Electric-Welding, Electrical Equipment for Gas Automobiles, Thawing Water Pipes, Marine Applications, Electricity in the U. S. Army, Electricity and Plant Growth, Windmill Electric Plants, Ozone Production, Radioactivity and the Electron Theory, Roentgen Rays, Lightning Rods, Electrostatic Machines, Electric Pianos, Players, Telegraphone, Telharmonium, Train-lighting Systems. Compasses, Static Electricity in Industrial Equipment, Specifications and Contracts.

SECTION 23

MECHANICAL SECTION. Compiled from standard authorities

Elements of Sections, Beams, Columns, Shafting, Gearing, Chain Drives, Belts, Rope Drives, Pipe and Screw Threads.

SECTION 24

STANDARDS OF THE AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS. Approved edition of 1921

SECTION 25

GENERAL ENGINEERING ECONOMICS AND CENTRAL STATION ECONOMICS. By Frank F. Fowle, S.B., and James Raley Cravath

General Engineering Economics, Definitions, Value, Price, Cost, Capital, Rent, Interest, Annual Charges, Depreciation, Social-economic Investigations, Valuation and Rate Making; Central Station Economics, Factors Relating to Utilization of Investment, Factors Relating to Territory Served, Typical Earnings of Companies, Rate Making and Valuation.

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SECTION 1

UNITS, CONVERSION FACTORS, AND TABLES

BY ARTHUR E. KENNELLY, A.M., Sc.D.

Professor of Electrical Engineering, Harvard University, and Mass. Inst. Technology; Past President, American Institute of Elect. Engineers; Illum. Engineering Society and Inst. Radio Engineers; Honorary Member, Institution of Elect. Engineers, London

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SECTION 1

UNITS, CONVERSION FACTORS, AND TABLES

SYSTEMS OF UNITS

1. Nature of units. Engineering makes use of physical quantities the broadest sense of that term, *i.e.*, including mechanical, chemical, physi thermal and physiological quantities. In order adequately to compare magnitudes of physical quantities of the same kind, unit magnitudes, units, are necessary for each kind of physical quantity dealt with.

2. Classification of units. The subdivisions and species into wh units may be divided are indicated in the scheme shown in Fig. 1, with planations which follow in Par. 3.

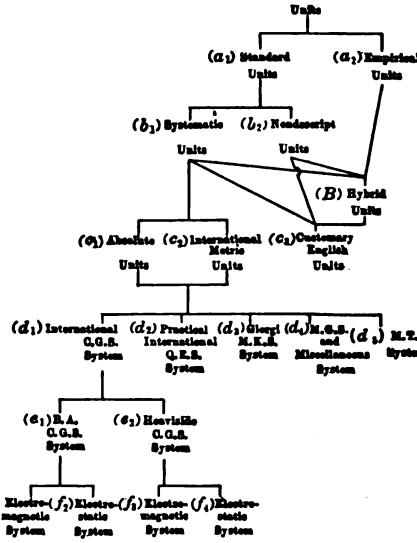


FIG. 1.

3(a_1) Standard units (see Fig. 1) may be said to include all units wh have received the stamp of recognition in technical literature.

3(a_2) Empirical units, on the other hand, are units which have spru into existence locally, ordinarily without any pretense to scientific deri tion, and which have not been sanctioned by general usage. At vari times during recorded history, empirical units have appeared. Thus, the early history of electrical units, a unit of conductor resistance was usec representing the resistance of a certain length of a certain size of telegra

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re, as embodied in a certain standard resistance coil. Similarly, the
erage e.m.f. of a Daniell cell was originally an empirical unit e.m.f.
1(b1) **Systematic units** are units of any definitely related group. Thus
units "pint," "quart," "peck," and "bushel" entering into "dry meas-
" are systematic units; because they stand in definite quantitative mutual
ation as a group or system. Again, the units "mill," "cent," "dime,"
"dollar" entering into American currency are systematic units.
1(b2) **Nondescript units** may be defined as standard units which are
systematic, or do not enter into any unit system. Thus, in Pennsylvania,
"bushel" of coarse salt, as a weight-unit, is 80 lb. avoirdupois,* but in
nois it is 50 lb. avoirdupois.
1(B) **Hybrid units,** in contradistinction to systematic units, are units
ich do not belong to any one system, but which are derived say from
durality of different systems; from a systematic and a general unit;
from any combination of standard and empirical units. Thus, a "kilo-
m" may be defined as a unit of weight in the international metric system;
ile a "square foot" is a unit of area in the customary English system.
the "kilogram-per-square-foot," as a unit of weight loading of floor-area,
hybrid unit. Occasionally the advantage of practical convenience in
use of a hybrid unit may outweigh the disadvantage of its unsystematic
ivation. No stigma necessarily attaches to the use of a hybrid, as distin-
shed from a systematic unit; but great caution has to be used in pursuing
and unfamiliar quantitative reasoning processes involving hybrid units,
numerical errors be introduced by neglect of coefficients.
1(a) **Absolute units** are units of physical quantities selected in a compre-
nsive scientific system based upon three or more fundamental physical
perties, such as length, mass, time, energy, specific gravitational force,
so that simple and fundamental quantitative relations may subsist
ween the members of the system and that each physical quantity may have
and only one unit in the system. The particular basic units from which
ystem of absolute units is derived are called the **fundamental units**
that system;† while the units so derived are called the **derived units** in
relation thereto. In a **dynamical system,** the **fundamental units**
three only and are: a unit of **length,** a unit of **mass,** and a unit of
me.‡ Consequently, unless otherwise specified, the term "absolute units"
taken as referring to a scientific system based on fundamental units of
gth, mass, and time. But whereas only one set of fundamental units has
se into recognition—the length-mass-time set above mentioned—several
ces of this set have been used to some extent; namely, the "foot-grain-
ond" system, § the "meter-kilogram-second" system, the "**centimeter-**
m-second" (**C.G.S.**) system, the "**meter-ton-second**" (**M.T.S.**)
tem, and the "**quadrant-eleventh-gram-second**" (**Q.E.S.**) system.
y the last three have come into extensive practical use. The C.G.S.
tem has become the international scientific system, and the Q.E.S.
tem an international electromagnetic system in electrical engineering.
complete electromagnetic absolute system involves five fundamental
ts, two of which may be constants of the ether.
1(c) **Metric units** are units pertaining to the **international metric**
tem. This system, which was created in France in 1792, was adopted
France in 1840, ‖ in Germany in 1872, in Austria in 1876 and so on from
civilised country to another; until at the present date, the only great
mmunities which have not yet adopted the metric system are the British
pire, the United States and the Russian Empire. The advantage of
system is its simplicity. It is a decimal system, using a single funda-
ntal unit of length (the meter) and one of mass (the gram). The **decimal**
ltiples of these are distinguished by Greek and Latin **prefixes** common to
branches of the system (**Par. 102**).

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* "The World Almanac," 1920, New York, p. 84.
† Everett, J. D. "C.G.S. System of Units," Macmillan Co., 1891, p. 15.
‡ Strictly speaking, a dynamical system of absolute units may employ
y desired acceleration as unit acceleration, when the unit force acts on
it mass, yet, if the unit of acceleration be the unit of length per unit of
e squared as in the C.G.S. system, the system is called an absolute kinetic
tem.
§ "British Association Report on Electrical Standards," 1863.
‖ Hallock and Wade. "Evolution of Weights and Measures and the Metric
tem," Macmillan Co., New York, 1906.

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3(c$_3$) Customary English units are the units of the English and Ame can measures, viz., length measure, square measure, land measure, cul measure, cord measure, dry measure, liquid measure, avoirdupois weig troy weight, apothecaries weight and jeweler's weight. Each of these me ures may be regarded as a system. The complete list may be regarded a congeries of imperfectly connected systems. Empirical and hybrid units mingled with the rest.

3(d$_1$) C.G.S. units are the units of that particular system of absol units which is based on the **international centimeter**, the **internatio gram** and the **mean solar second.** That is, they are absolute un employing the metric system in a definite way. A reason for the centime having been selected in place of the meter as the fundamental unit of leng was that the mass of the cubic centimeter of water (at the temperature unit density) is the gram or unit mass; whereas the mass of a cubic meter water would be a metric ton as in the M. T. S. system.

3(d$_2$) Q.E.S. units are units pertaining to the quadrant-eleventh-gra second absolute system; *i.e.*, the system in which the unit of length is cm. or 1 theoretical quadrant of the earth as measured from a pole to equator, the unit of mass is 10^{-11} g.,* and the unit of time the mean so second, or the 1/86,400th part of the annual mean daily period of re lution of the earth with respect to the sun. This is the system to which international ohm, volt, ampere, joule, watt, coulomb, farad and hen belong. The system was not intentionally established as a Q.E.S. syste but the ohm having been arbitrarily selected, for convenience of magnitu as 10^9 C.G.S. electromagnetic units, and the volt similarly as 10^8 C.G units, the rest of the system necessarily coincides with the Q.E.S. syste or is such a system as would be produced by the selection of the quadra eleventh-gram and second as fundamental units, together with unity the permeability and unity for the dielectric constant of the ether.

3(d$_3$) Giorgi units are units in a combined absolute and practical syst devised by Prof. G. Giorgi,† in which the fundamental units are: the met kilogram-second-international ohm, and the further assumption that permeability of free ether, instead of being unity as in the C.G.S. magne system, is $\mu_o = 4\pi \times 10^{-7}$ henry/m. On this basis the ohm-volt-amp series of practical units become also absolute units. The electric inductivi instead of being unity, as in the C.G.S. electric system, becomes $k_o = 1/3 \times 10^{-9}$ farad/m. No distinction arises in the Giorgi system between elect and magnetic units. The system is also rectified in regard to 4π facto or is **"rationalized"** in the Heaviside sense; so that a number of fundamen equations in the system differ from those of the C.G.S. system in regard such 4π factors.

3(d$_4$) M.G.S. units, etc. Units in an absolute system whose fundamen units are the meter-gram-second, the millimeter-milligram-second, the fo grain second, etc. None of these extraneous absolute systems have co into extensive use.

3(e$_1$) B.A. units are the units of the C.G.S. system as established by British Association for the Advancement of Science‡ in 1862. The elect static subsystem was established on the basis of the unit quantity of el tricity such that it repelled its prototype at a distance of 1 cm. with a fo of 1 dyne. The electromagnetic subsystem was similarly established on basis of the unit magnetic pole such that it repelled its prototype at a d tance of 1 cm. with a force of 1 dyne. This procedure led to the anomal result that every electromagnetic quantity has a unit both in the elect static subsystem and in the magnetic subsystem.

3(e$_2$) Heaviside units are units in that form of the C.G.S. system wh was first suggested by Mr. Oliver Heaviside in 1882.§ He showed that unit electric point charge and a unit magnetic point pole had been respe ively defined such that unit total flux emanated therefrom, the strength

* Maxwell, J. C. "A Treatise on Electricity and Magnetism," 18 Chapter X.

† Ascoli, M. "On the Systems of Electrical Units," Trans. Int. Electri Congress of St. Louis, 1904, Vol. I, p. 130.

‡ "British Association Report on Electrical Standards," 1863.

§ Heaviside, O. "The Relations between Magnetic Force and Elect Current." The Electrician, London, Nov. 18, 1882.

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he field at unit distance would be $1/(4\pi)$, and this, not unity, should be the force in dynes that the prototype would develop in repulsion. As a consequence of this unnatural definition of the B.A. unit charge and pole, the fundamental equations of the B.A. system become interlarded with 4π-factors in rectilinear problems and denuded of them in spherical problems where they should naturally be expected to occur. Mr. Heaviside proposed to rectify the system by changing the fundamental definitions in the manner suggested, and enunciating a new list of units in both the electrostatic and magnetic subsystems; all related to the corresponding B.A. units in simple powers or roots of 4π. He similarly proposed rectifying the practical or Q.E.S. system of units by adopting a new ohm, volt, ampere, etc., all bearing some ratio of simple power or root of 4π to the corresponding existing values. If Mr. Heaviside's proposals had been formulated and considered prior to international adoption of the ohm-volt-ampere series of units, and realised standards, they might have been adopted.* At the present time a very few physicists employ Heaviside's "rational" units in theoretical analysis.†

4. **Fundamental principles concerning units in equations.** Many of the equations representing propositions in pure mathematics may be satisfied by quantities of any kind. Thus taking the very simple equation

$$2(a+b)=2a+2b$$

it is clear that the quantities a and b may be of the same kind or of different kinds, and their respective units may be any whatsoever, without affecting the identity expressed, so long as a and b have respectively the same meanings on the two sides of the equation. When, however, as ordinarily in engineering, physical magnitudes are dealt with in an equation; then three consequences ensue; namely:

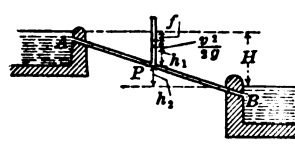


FIG. 2.

(1) *The equation can only be interpreted in terms of some unit of the particular physical quantity dealt with.* This is the unit of the equation.

(2) *The unit employed on each side of the equation must be the same.*‡

(3) *If either side of the equation consists a simple sum of positive or negative terms; then each of these terms must employ the same unit as the equation.*

For example, considering the case of a uniform pipe, discharging water at a uniform velocity v meters per sec., from a reservoir A into a river B (Fig. 2). Let H be the total head or elevation in meters between the water levels A and B at the two ends of the pipe, and let a vertical pressure pipe be inserted (Fig. 2) at any point P. Then we have the well-known hydraulic relation:

$$H=f+\frac{v^2}{2g}+h_1+h_2 \qquad \text{(meters)} \qquad (1)$$

where f is the loss of head due to friction in the length of pipe AP, g is the acceleration due to gravitation in meters per second per second, $v^2/2g$ is the loss of head due to velocity at the point P, h_1 is the remaining head above the local level, and h_2 the height of P above the reservoir level at B. Then according to the propositions above stated, each of the four terms on the right hand of the equation must be a head, or height, in meters, and both sides of the equation must be expressed in terms of the same unit. The left-hand term H cannot be in meters and the right-hand terms or any of them in feet or centimeters. The second term on the right hand ($v^2/2g$) contains a velocity v, and an acceleration g; yet the term as a whole must be a height, if the equation is correct.

The equation might evidently be expressed in terms of any unit of length such as inches, feet, cubits, yards, miles or millimeters. As an algebraic equation entirely by itself, there is no reason for selecting one unit rather

*Heaviside, O. "Electrical Papers." Macmillan Co., 1892, Vol. II, p. 575.
†Lorentz, H. A. "The Theory of Electrons." B. G. Teubner, 1909, p. 2.
‡An exception is found in an equation expressing the relation between different units of the same species, as for example, in the equation 1 lb. = 16 oz.

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than another. The numerical values applying to any particular case c ered by the equation will vary greatly according to the unit selected. however, any one of the terms is expressed in a particular unit, all the ot terms must adopt the same unit. In all cases, however, it is helpful to reader to have the unit of the equation written out at the end of its line above, in order to assist the numerical interpretation.

HISTORICAL SKETCH OF ENGLISH UNITS

5. The English weights and measures are based upon old Ron weights and measures.* The **troy pound** is supposed to have been a wei of silver referred to as a "pound sterling." This pound would be coined i 240 silver pennies or "pennyweights," each of 24 gr. (barley grain weigh It would, therefore, contain 5,760 gr. Heavy bodies (substances in gr outside of coins or bullion) were weighed by "avoirdupois" weight, authori by law early in the fourteenth century. Several slightly different avoir pois pounds were in use. Since Queen Elisabeth's reign the avoirdu pound has been fixed at 7,000 troy grains.

6. In regard to British lengths, the earliest seems to have been **cubit** or half yard. The cubit is a very ancient measure, and correspond a forearm length from elbow to middle finger-tip. The royal iron stand **yard** was constructed in the thirteenth century, after which the cubit or h yard gradually fell out of use. The **foot** was standardized at one-third the yard. The mile was a relic of the Roman "millia passuum," or thous paces; the Roman pace was two of our paces, or counted between the lift one and the same foot.

7. Gallon measures of volume existed at different times in England six different forms, such as the corn-gallon, the ale-gallon, etc. Among th the wine-gallon of Queen Anne contained 231 cu. in. This gallon was brou to America by the early colonists and remains to-day the U. S. gallon. 1824, the British enacted a new "**imperial gallon**" to supersede all existing gallons, and defined it as the volume of 10 avoirdupois pounds distilled water at the temperature of 62 deg. fahr. with the barometer 30 in. It was further defined as a measure containing 277.274 cu. in. distilled water. There is thus a **difference between British and Americ gallons** in the ratio 277.274 to 231 = 1.204 : 1; so that the British gall quarts, and pints are respectively about 20 per cent. larger than Ameri gallons, quarts and pints, a large discrepancy that has frequently led misunderstandings.

8. In land measure, since Anglo-Saxon times, a "**perch**" or "**pol** was 11 **cubits** in length = 16½ ft., and such a pole was the **surveyor's un** A length of 40 perches was a **furlong,** and 8 furlongs the **statute mi** An **acre** of land was the area of a rectangular strip a furlong in length 4 perches in breadth, which breadth was known as the "**acre's breadth**" An acre therefore included 40×4 = 160 sq. perches. Eight such stripes to end made the statute mile, and 80 such strips side by side made a stat mile breadth; so that a **square statute mile** contained 640 acres. Ea in the seventeenth century, Prof. Edmund Gunter of Gresham Coll decimalized acre measure by inventing a 100-link "**chain**" of outstretch length equal to 4 perches or the acre's breadth (66 ft.). The acre thus beca 10 sq. chains.

HISTORICAL SKETCH OF THE INTERNATIONAL METRIC SYSTEM

9. Prior to 1790, differences existed between the weights and measu of different Departments of France. Reform in the directions of simp fication and unification was promised in a decree of the National Assem under the sanction of Louis XVI in 1790. The metric system was actua developed under the authority of the French Republic in 1793, in the ha of a committee of scientists and engineers.

10. The decimal system, at the base of the metric system, was origina extended to angles and to time, the right angle being divided into 100 grad each subdivided into 100 min. and again into 100 sec. The day was divid into 10 hr., each subdivided into 100 min. and again into 100 sec. The de mal subdivision of time never came into extended effect, and the decim subdivision of angles has only been used to a limited extent, except in Fran

* Watson, Sir C. M. "British Weights and Measures." London, 191

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11. **The meter was selected as a length equal to the ten millionth part the northern quadrant of the earth,** or distance from pole to equator the meridian of Paris. Later measurements have shown that the international standard meter finally adopted is shorter than the 10^{-7} quadrant 0.02* per cent. The advantage of such a basis for the meter is that by use of the decimal subdivision of angles; *i.e.*, by the substitution of 100 ades for 90 deg., the kilometer becomes the natural nautical unit of dis-ace, or the hundredth of the grade; just as the English nautical mile is sixtieth of a degree.

12. **The metric system** is universally used in all European countries, cept Great Britain and Russia. The quantitative literature of the scien-ic world is almost exclusively written in the metric system. To express antitative relations exclusively in the English units is to conceal their aning, to a great extent, from all but English-speaking peoples; and also discredit them scientifically, by implication.

13. **In the United States,** the metric system has been a legally recognised tem since July 28, 1866. In 1893, the U. S. Office of Standard Weights d Measures was authorised to derive the yard from the meter† at the ratio yd. = 3600/3937 meter. The customary weights are likewise referred to kilogram. The customary weights and measures of the United States thus defined in terms of, and maintained with reference to, the inter-tional metric system.

14. **The international metric standards,** *i.e.*, the standard meter r and the standard kilogram, are maintained at the International Bureau Weights and Measures at Sèvres, near Paris, France, in a building which s been declared internationally neutral or outside of French territory. opies or prototypes of these standards are maintained at the various tional laboratories and are occasionally intercompared.

EVOLUTION OF THE PRACTICAL ELECTROMAGNETIC SYSTEM OF UNITS‡

15. **Brief historical outline.** In 1861 a committee of the **B.A.** (British sociation for the Advancement of Science) was appointed to consider tandards of electrical resistance. The committee decided to adopt a series f electrical units in the C.G.S. absolute system. The unit of resistance in he C.G.S. magnetic system was so small (one-billionth of an ohm) that it as considered unfit for practical use and a unit 10^9 times greater than the .G.S. unit was selected as of convenient magnitude. This decimally derived nit was called the ohm after the German scientist Dr. Ohm. Similarly, he C.G.S. magnetic unit of electromotive force was regarded as unfit for ecommendation, and a unit 10^8 times greater than the C.G.S. unit was elected, and called the volt, after the Italian electrician Volta. The ohm aving been selected as a unit, standard resistance coils had to be produced nd adjusted—a work of great labor. In 1864 and 1865, certain standards f resistance or **B.A. ohms** were produced and put into service. In 1872, Ir. **Latimer Clark** produced the well-known **zinc-mercury standard cell** hich bears his name.

16. **B.A. ohm too small.** In 1878, it was realized that the B.A. ohm as too small by over 1 per cent. That is, the B.A. ohm is now taken to e **0.9866** of the existing **international ohm.**

17. **In 1881 an international electrical congress** at Paris recommended hat the standard ohm should be represented as the resistance of a uniform olumn of mercury, 1 sq. mm. in cross-section, at 0 deg. cent., the length of uch a column for the B.A. ohm being approximately 104.9 cm. The Paris ongress of 1881 also adopted the ampere, coulomb and farad, as the prac-ical units of current, quantity and capacity. The practical system based n the ohm and volt thus became virtually the Q.E.S. (quadrant-eleventh-gram-second) system, in place of the C.G.S. system; *i.e.*, as though 10^9 cm. ere substituted for 1 cm. as the unit length, and 10^{-11} g. instead of 1 g. as the unit mass.

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*Annuaire pour l'an 1913, Paris. Gauthier-Villars.

†Tables of Equivalents of the U. S. Customary and Metric Weights and Measures. Department of Commerce and Labor, Bureau of Standards, Publication.

‡Wolff, F. A. "The So-called International Electrical Units." Trans. Int. El. Congress, St. Louis, 1904, Vol. I, p. 148.

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18. In 1882, an international commission met at Paris and ado a length of 106 cm. as the length of the mercury column defining the ohm, closer approximation to the true ohm than the B.A. ohm. This 106 ohm was called the **"legal" ohm,** as distinguished from the B.A. o Legal ohms, volts, etc., have at the present date almost completely appeared. They represented an intermediate stage of approximatio the present international unit values.

19. In 1889, an international electrical congress at Paris ado the joule, the watt, and the quadrant, as the practical units of energy, po and inductance, respectively.

20. Edinburgh conference. In 1892, a conference was held in con tion with the B.A. meeting at Edinburgh. It was then decided to ad 106.3 cm. as the length of mercury column whose resistance should emb the ohm.

21. In 1893, the international electrical congress of Chicago ado the 106.3-cm. ohm, which was called the **international ohm.** The o units of the practical system adjusted in conformity to this value were ca correspondingly the **international ampere, volt, coulomb,** etc. name of the unit of inductance was changed from the quadrant to the **hen** in honor of the American physicist of that name.

22. In 1900, an international electrical congress at Paris, after s debate, adopted the **maxwell** as the unit of magnetic flux and the **ga** as the unit either of magnetic intensity or of flux-density in the C.G.S. n netic system.

23. In 1908, an international commission at London considered **order of sequence of** resistance, current and voltage **standards,** wh had been left indefinite at preceding congresses. It was decided that **ohm** should be the **first unit,** and the **ampere the second,** as determi by the rate of electrodeposition of silver under specified conditions. volt was to be determined from the ohm and ampere.

DEFINITIONS OF FUNDAMENTAL UNITS

24. Length. (*L.*) Linear distance between any two points. The uni length in the metric system is the **meter,** in the C.G.S. system the **cen meter,** in the customary system it is any one of the following:—inch, fo yard, pole, furlong, statute mile, nautical mile.

The fundamental unit of length of the United States is the internatio meter, the primary standard of which is deposited at the Internatio Bureau of Weights and Measures near Paris, France. This is a platinu iridium bar with three fine lines at each end; and the distance between middle lines of each end when the bar is at the temperature of 0 deg. ce and is supported at the two neutral points 28.5 cm. each side of the centr 1 m. by definition. Two copies of this bar (prototype meters) are in possession of the United States and are deposited at the Bureau of Standa

The United States yard is defined by the relation

$$1 \text{ yd.} = 3600/3937 \text{ m.}$$

The legal equivalent of the meter for commercial purposes was fixed 39.37 in. by the law of July 28, 1866, and experience having shown that value was exact within the error of observation, the United States Office Standard Weights and Measures was, by executive order in 1893, authori to derive the yard from the meter by the use of this relation.

25. Mass. (*M.*) The quantity of matter in a body is estimated either its inertia or by its weight. In the metric system, the unit of mas the **gram,** which was originally defined as the mass of a cubic centim of distilled water at 0 deg. cent., although in practice it is taken as thousandth part of a standard kilogram. In the customary system, unit is ordinarily any one of the following: avoirdupois grain, ounce, pou or ton (long or short); occasionally, it is one of the Troy system (ou pound). In the use of drugs, it is usually stated in apothecaries weight. mass of precious stones is commonly estimated in carats.

26. Time. (*T.*) The interval elapsing between any two events. In C.G.S. system, the unit of time is the **mean solar second,** or 86,400th p of the mean solar day. In the customary system, it is either the second, m ute, hour, day, week or year of mean solar time.

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27. Area. (*A.*) Space occupied in two dimensions. In the metric system, the unit is primarily the **square meter**; but the square dekameter or are is used in land measure; while square millimeter; square centimeter; and square decimeter are also used. In the customary English system the unit may be the square mil, the square inch, square foot, square yard, square chain or square mile.

28. Volume. (*V.*) Space occupied in three dimensions. In the metric system, the unit is primarily the **cubic meter** or **stere**; but the cubic decimeter or **liter** is much used, as well as the cubic centimeter and the cubic millimeter. In the customary English system, the units are the cubic inch, cubic foot, cubic yard, cubic mile.

29. Density. (δ.) Ratio of mass to the volume it occupies. In the metric system the unit is primarily the gram per cubic meter; but decimal derivatives are more common. In the C.G.S. system, the unit is the **gram per cubic centimeter**. In the M.T.S. system, it is the ton per cubic meter.

30. Force. (*F.*) That which tends to change the energy existing in a given region of space. In mechanics, force is that which tends to produce change of motion in matter. In the C.G.S. system, the unit is the **dyne**, or that force which after acting on a free gram during 1 sec., creates therein a velocity of 1 cm. per sec. In mechanics, the unit force is the force required to support unit mass against standard gravity; *i.e.*, gravity at the standard locality; the weight, at standard latitude and level, of a gram, a kilogram, a pound, etc., according to the system considered. In the M.T.S. system, the unit is the sthene, or the force which acting on a metric ton accelerates it one meter per second.

31. The weight of a body is the **gravitational force** acting upon it. Its standard weight is its weight under standard gravitational force. Its local weight is its weight under local gravitational force. In the C.G.S. system the unit for weight is the **dyne**. It is also expressible in the various systems as the gram weight, kilogram weight, the pound weight, etc.

Important differences of usage and terminology frequently exist between text-books on physics and text-books on applied mechanics, in regard to the units of mass and of force. These differences are not essentially connected with English weights and measures, because they exist in the text-books of several European countries where the metric system is exclusively employed. In physics, it is customary to regard the terms gram, milligram, kilogram, pound, etc., as designating a mass in the sense above defined. The force exerted gravitationally on such a unit is called the weight of the unit, and is derived from the product of the mass and the gravitational acceleration constant g. Thus in an absolute kinetic system, if a body has a mass of m grams, its local weight or gravitational force F is

$$F = mg \qquad \text{(dynes)} \qquad (2)$$

g being the local gravitational acceleration. If the body is transferred to a place where there is standard gravitational acceleration g_0, then:

$$F_0 = mg_0 \qquad \text{(dynes)} \qquad (3)$$

In applied mechanics, it is customary to regard the terms gram, kilogram, pound, etc., as designating a weight or gravitational force in the sense above defined; that is, to say one and the same term, "kilogram" say, is used with a different meaning in the two cases here compared. If a body has a standard weight of W_0 grams, then by (3),

$$F_0 = (W_0/g_0)g_0 \text{ (grams standard weight)} \quad (4)$$

so that in the books on applied mechanics, where a mass has to appear in an equation, it is represented by such a term as W_0/g_0. The same is true for any system of units. Thus in (3), if m is a mass expressed in pounds, and g_0 is the gravitational constant in customary measure, then we might find in a text-book on physics:

$$F_0 = mg_0 \qquad \text{(poundals)} \qquad (5)$$

whereas in a text-book on applied mechanics (4) would have to be written

$$F_0 = (W_0/g_0)g_0 \text{ (standard pounds weight)} \quad (6)$$

The centrifugal force of a mass m pounds whirling with a peripheral velocity v feet per sec. at a radius of r feet would be, according to (5)

$$F = m\,(v^2/r) \qquad (\text{poundals}) \qquad (7)$$

*Everett. "C.G.S. System of Units." Macmillan Co., N. Y. 1891, p. 28.

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a **poundal** being the force which acting on a pound mass for 1 sec., devel in it a velocity of 1 ft. per sec. A pound weight is equal to 32.2 pound But if we consider a pound to be a force, represented by a weight W,

$$F = \frac{W}{g} \cdot \frac{v^2}{r} \qquad (\text{* pounds force})$$

It is evident that there is no difference between the two contrasted modes presenting the facts, provided that we distinguish carefully between **"pound-mass"** and a **"pound-force."** If, however, we use the same w "pound" to do duty in the two cases, contradictory and illogical results m be obtained.

It follows that the terms **gram, kilogram, pound, ton,** etc., are s ceptible of either of **two distinct meanings**; namely, a **unit of mass** matter or a **unit of force** equal to the gravitational force exerted on t mass by the earth. Confusion can be avoided in all cases, however, by usi distinguishing terms, as "gram-mass," "gram force," or "gram weight."

32. Linear velocity (v). Rate of movement along a line, and ordinar along a straight line; also, time rate of change of space. The unit in C.G.S. system is the centimeter-per-second, in the metric system the met per-second, or per minute or per hour. In the customary system, it wo be any of the customary English units of length per second, minute, h or day, etc. Velocities may be either + or − with respect to a select point on the line of motion.

33. Linear acceleration (a). Time rate of change of linear veloci The C.G.S. unit is the **(cm. per sec.) per sec.**; or the cm. per sec.². T metric unit may be a meter per sec.², or a meter per hour², or any decim derivative of the meter, per square of the second, minute, hour, etc. useful hybrid unit is the (kilometer per hour) per second. Acceleratio may be either + or −.

34. Plane angle (α, β, γ). In plane circular trigonometry, the ratio a circular arc to its radius. The C.G.S. unit is the **radian,** or 1 cm. of drawn with a radius of 1 cm. The metric unit is the **grade** or one-hundred of the quadrant with unit radius. The customary unit is either the degree one-ninetieth of the unit-radius quadrant—or the revolution of f quadrants.

35. Angular velocity (ω). In plane circular trigonometry, the time rat change of angle at any given instant. The C.G.S. unit is the **radian p second.** The customary unit is either the degree per second, or the revo tion per second, or per minute, etc. Angular velocities may be either + or

36. Angular acceleration. In plane circular trigonometry, the ti rate of change of angular velocity. The C.G.S. unit is the **radian per secon per second.** Customary units are the degree per sec.², the revolution sec.², or per min.², etc.

37. Energy (W). The capacity of doing work. Energy may be con ered as the fundamental entity in terms of which all dynamical quanti may be defined. In the C.G.S. system, the unit is the **erg, or dyne-cen meter.** In mechanics, it may be any product of a unit weight and distance such as kilogram-meter, foot-pound, etc., according to the syst An industrial unit in the meter-kilogram-second system is the **watt-hou**

38. Power (P). Activity or the rate of working. The rate of expend energy. The C.G.S. unit is the **erg per second.** The metric gravitati unit is the gram-meter per second, or a decimal derivative, such as the k gram-meter per second. The absolute unit in the meter-kilogram-sec system is the **watt.** The customary unit is the **foot-pound per secon** or the **horse-power** of 550 ft.-lb. per sec. It may be either local standard.

39. Momentum. The product of the mass of a body and its veloc The C.G.S. unit is the **gram-centimeter per second.** A customary is the pound-mass × (foot per second).

40. Torque (τ). Twisting effort. The moment of a twisting co ordinarily exerted about a shaft axis. The C.G.S. unit is the **dyne-perp dicular-centimeter**; *i.e.*, a dyne acting at right angles to a radius arm 1

* Prof. W. J. M. Rankine. "Applied Mechanics," 9th edition, 1877, page

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length. The customary unit is the **pound-weight perpendicular foot.** The word "perpendicular" is omitted from the unit, care must be taken to distinguish from a dyne-centimeter or a foot-pound weight, which are units of work or energy. A torque is not a work, and can do no work until it traverses through an angle.

41. **Pressure (p).** A force integral, or summation of a force, over a surface. A pressure may be either total or specific. A **total pressure,** as the name suggests, is the force integral or **total force** with reference to some particular direction or set of directions. A **specific pressure,** or intensity of pressure, is the ratio of a pressure to the surface area over which it is applied, or the **pressure per unit area.** Unless otherwise specified, a pressure is ordinarily understood to be a specific pressure. The C.G.S. unit of pressure is the **dyne per square centimeter,** sometimes called a "**bar.**"* The metric gravitation unit is the **gram weight per square meter,** or some decimal derivative, such as the kilogram weight per square millimeter. **The standard atmospheric pressure** of 760 mm. mercury at sea-level and 0 deg. cent. at latitude 45 deg., is 1.01321×10^6 bars or 1.01321 megabar.† Pressures are thus frequently reckoned in atmospheres. They are also frequently expressed as heights of a column of uniform liquid.

42. **Strain.** A change in the shape or size of a body due to the application of a force or set of forces. In the simplest cases, strains are (1) voluminal expressions or dilations; (2) extensions or compressions in one direction with corresponding lateral compressions or dilations (such an extension is called an elongation); (3) a twist or shear. These various strains, when small, are expressed as small numerical fractions, in which the numerator expresses the distortion and the denominator the original undistorted value. These strains are ordinarily independent of the system of units employed.

43. **Stress.** The force or set of forces applied to a body, and which tend to produce a strain. They may be either simple forces, pressure intensities, twists, or combinations of the foregoing, and are expressible in the corresponding units.

44. **Young's modulus of elasticity.** The specific tension which would have to be applied to a uniform prism of a substance in order to double its original length, as judged from a small extension under a measured tension. It is a specific tension or a longitudinal force per unit area of prism. The C.G.S. unit is the **dyne per square centimeter.** The metric gravitation unit is the **gram-weight** per square meter or some decimal derivative. The customary unit is the **pound-weight per square inch.**

45. **Moment of inertia of a body with respect to an axis (J).** The product of the mass of the body and the square of its radius of gyration with respect to the axis considered. It is therefore the product of a mass and a distance squared. The C.G.S. unit is the **g-cm.²** The metric unit is the gram-mass-meter.² A customary unit is the **pound-mass-foot.²** The **radius of gyration** of a body with respect to an axis is the square root of the mean square of the distances of all the particles of the body from the axis. It is therefore a length. The C.G.S. unit is the centimeter. A metric unit is the meter, or decimal derivative. A customary unit is the foot.

DEFINITIONS OF ELECTRIC AND MAGNETIC UNITS

46. **Electric quantity (Q).** The amount of electricity present in any electric charge or passed through a circuit during any time interval by an electric current. The practical unit is the coulomb, the C.G.S. units are the abcoulomb and statcoulomb.

47. **Electric e.m.f. or pressure (E).** That which tends to make an electric current flow. E.m.f. is ordinarily accompanied by a difference of electric potential; but an e.m.f. may occur without difference of potential, as for example, when a straight bar magnet is thrust symmetrically into a circular loop of uniform wire. A brief current will thus be set up in the wire due to an e.m.f. induced by the magnet's motion; but there will be no difference of electric potential in or around the wire. The practical unit is the volt. The C.G.S. units are the abvolt and statvolt.

* Richards and Stull. Carnegie Institution Publication No. 7, p. 43, Dec., 1903.

† Gauthier-Villars. "Les Récents Progrès du Système Metrique." Paris, 1907, pp. 30–31. Meteorologists commonly call this 1.01321 bars.

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E.m.f. may be reckoned for a complete circuit or for any portion th
that is, each and every portion of a closed circuit in the steady state
Ohm's law.

48. Potential difference (U or V). A condition in virtue of wh
electric current tends to flow from a place of higher to a place of lower
tial. The numerical measure of the potential difference is the work d
a unit quantity of electricity in passing between the two points. Th
tical unit is the **volt.** The C.G.S. units are the abvolt and statvolt.

49. Potential gradient. The space rate of change of potential,
change with respect to distance. An electric potential gradient is the
rate of change of electric potential, and similarly for magnetic, ther
gravitational potential. The systematic unit in the practical system
volt per quadrant, but a hybrid unit such as **volt per centimeter** is
ally used. The C.G.S. unit is either the **abvolt or statvolt per cm.**

50. Electric current (I). The rate at which electricity flows thro
conductor or circuit. The practical unit is the **ampere,** which is a c
of one coulomb per second. The C.G.S. unit is either the **absamp**
statampere.

51. Electric current density. The ratio of the current flowing th
a conductor to the cross-sectional area of that conductor. More st
the current density at a point in a conductor is the ratio of the current th
a very small plane element of section containing the point and perpend
to the current, to the area of the element. The systematic practical
the **ampere per square quadrant.** In practice, a hybrid unit is pre
such as the **ampere per square centimeter** or square inch. The
unit is either the absampere or statampere per square centimeter.

52. Electric resistance (R). Obstruction to electric flow. The
of voltage to current in a conductor or closed circuit. The practical
the **ohm.** The C.G.S. unit is either the **absohm or statohm.**

53. Electric resistivity (ρ). The ratio of potential gradient in
ductor to the current density thereby produced. Also the specific resista
a substance numerically equal to the resistance offered by a unit cube
substance as measured between a pair of opposed parallel faces. Th
tematic practical unit is the **ohm-quadrant** or numerically equal
resistance in a cubic earth-quadrant. A hybrid unit such as the **ohm**
is usually preferred. The C.G.S. magnetic unit is the absohm-cm. Se

54. Electric conductance (G). The conducting power of a cond
or circuit for electricity. The inverse or reciprocal of electric resis
The practical unit is the **mho.** The C.G.S. unit is either the **abmho**
statmho.

55. Electric conductivity (γ). The specific electric conducting
of a substance. The reciprocal of resistivity. The systematic pra
unit is the **mho per quadrant.** A hybrid unit, such as the **mho pe**
is usually preferred. The C.G.S. magnetic unit is the **abmho per cm.**

56. Inductance (L). The capacity for electromagnetic induction
sessed by an active circuit either on itself or on neighboring circuits.
ratio of the magnetic flux linked with and due to an active conductor
ber of turns × total flux) to the current strength carried. The pra
unit is the **henry.** The C.G.S. units are the **abhenry** and **stath**
The term "inductance" seems to have been first introduced by Heav
as a brief equivalent for "coefficient of self-induction." Inductance ma
divided into two species; namely, **self-inductance** and **mutual induct**
The unit is the same for both species.

57. Electric capacitance (C). Sometimes called **permittance** or
city. The power of storing or holding an electric charge. The ratio
electric charge on a conductor to the electric potential difference prod
the charge. The practical unit is the **farad.** The C.G.S. unit is eithe
abfarad or the **statfarad.** The term "permittance" was introduce
Heaviside.† It should be noted that capacitance is used by a few writ
synonymous with capacity-reactance.

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* Heaviside, O. "The Electrician," 1884, May 3, p. 583; also "Elec
Papers," Macmillan Co., 1892, Vol. 1, p. 354.

† Heaviside, O. "Electrical Papers," 1892, Vol. II, pp. 302 and 327.

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58. Permittivity is the specific permittance of a substance and numerically equal to the permittance offered by a unit cube of the material as measured between a pair of opposed parallel faces. In the C.G.S. electric system it is equal to k, the dielectric constant. Analogous to electric conductivity and magnetic permeability. A term introduced and defined by Heaviside.†

59. Dielectric constant or specific inductive capacity (k). The ratio of the capacity of a condenser whose coatings are separated by a given substance, to the capacity of a similar condenser whose plates are separated by a vacuum. A pure numeric in any system of units.

60. Elastance. The reciprocal of the capacitance of a condenser or dielectric. No unit for elastance has been agreed upon in any system. The term "**daraf**" has, however, been suggested for this unit in the practical system, so that a condenser having a capacity of one farad would also have an elastance of one daraf. The C.G.S. unit would be a statdaraf.

61. Elastivity. The specific elastance of a substance, and numerically equal to the elastance offered by a unit cube of the substance as measured between a pair of opposed parallel faces. In the C.G.S. electric system it is the reciprocal of permittivity. Analogous to electric resistivity.

62. Frequency (f). In a simple alternating-current circuit the number of cycles executed by the current per second. The unit is the **cycle per second.**

63. Angular velocity (ω) of a simple alternating-current circuit. The product of the numeric 2π and the frequency f of the current in cycles per second. The unit employed is the **radian per second.**

64. Reactance (X). In a simple alternating-current circuit, the reactive component of the impedance, as distinguished from the active component, or resistance. Reactance may be divided into two species of mutually opposite signs; namely, **inductive reactance** or that species of reactance developed in an inductance, $2\pi fL$, and **condensive reactance**, or that species of reactance developed in a condenser, $1/2\pi fc$. Inductive reactance is denoted (when using the method of complex imaginary quantities) by the sign $+j$ or $+\sqrt{-1}$, and condensive reactance by the sign $-j$ or $-\sqrt{-1}$. The unit of reactance in the practical system is the **ohm.** The C.G.S. unit is either the absohm or statohm.

65. Impedance (Z). The apparent resistance of an alternating-current circuit or path. The **vector sum** of the **resistance** and **reactance** of the path. The practical unit is the **ohm.** The C.G.S. unit is either the absohm or statohm.

66. Admittance (Y). The reciprocal of the impedance of an alternating-current circuit or path, a complex quantity. Units mho, abmho or statmho.

67. Conductance (G). In a direct-current circuit, the reciprocal of the resistance. The practical unit is the **mho.** In Germany it is called the Siemens. The C.G.S. unit is either the abmho or the statmho.

In a simple alternating-current circuit, the conductance is the active component of the admittance, or the quantity which multiplied by the root-mean-square impressed alternating voltage gives the active component of the root-mean-square current, or the component in phase with the e.m.f. The practical unit is the mho. The C.G.S. unit may be either the abmho or statmho.

68. Susceptance (B). The reactive component of admittance in a simple alternating-current circuit. The practical unit is the **mho.** The C.G.S. unit may be either the abmho or statmho.

69. Magnetic poles. Those portions of the surface of a magnetic source where the magnetic flux enters or leaves the surface. Magnetic poles appear wherever there is an abrupt change of permeability.

70. Magnetic pole strength. The total flux entering or leaving a pole divided by 4π. No name has been provided for this unit. The product of magnetic pole strength and the length of the magnet (interpolar distance) is the **magnetic moment.**

71. Magnetic flux (ϕ). The magnetic flow or current that passes through any magnetic circuit. The C.G.S. magnetic unit is the **maxwell.**

† Heaviside, O. "Electrical Papers." 1892, Vol. II, p. 329.

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72. Magnetic flux-density (ℬ). The ratio of the magnetic flux in an cross-sectional element of a magnetic circuit to the area of that elemen The C.G.S. magnetic unit is the **gauss**, which is also a maxwell per squa centimeter.

73. Magnetomotive force (m.m.f.). That which produces magneti flux. The analogue in the magnetic circuit of electromotive force in th electric circuit. No name has been provided for the unit of m.m.f. eithe in the practical or in the C.G.S. magnetic system. The name of **gilbe** has, however, been suggested for the latter. A convenient practical un is the **ampere-turn** which is $4\pi/10 = 1.257$ gilberts.

74. Magnetic field intensity (ℋ) or **gradient of magnetic potentia** also termed **magnetizing force.** The rate of change of magnetic potenti with respect to distance. In a region of unit permeability, the field intensit is numerically equal to the magnetic flux density. The provisional nam of the C.G.S. magnetic unit is the **gilbert per centimeter.** A numericall related hybrid unit is the **ampere-turn per centimeter.**

75. Reluctance (ℜ). Obstruction to magnetic flow. In a simple mag netic circuit, the ratio of the m.m.f. to the magnetic flux. A provision name for the C.G.S. magnetic unit is the **oersted.** One gilbert m.m.f. actin on a magnetic circuit of one oersted reluctance produces one maxwell of flu

76. Reluctivity (ν). A specific reluctance, numerically equal to th reluctance of unit cube of a substance between any pair of opposed paralle faces. The C.G.S. magnetic unit is the **oersted-cm.**

77. Permeance. The reciprocal of reluctance. Conducting power fo magnetic flux. No name has been adopted for this unit.

78. Permeability (μ). The reciprocal of reluctivity, or **specific perme ance.** No name has been adopted for this unit. In the dimensiona formulas of the C.G.S. system, if the electric and magnetic constants of th æther are considered as mere numerics; both permeability and reluctivit are also mere numerics. Also magnetic intensity has the same dimension as flux density;* so that on this basis, which was at one time undisputed there would be no difference between gilberts-per-centimeter and gausse except numerically. It is now generally admitted,† however, that the electri and magnetic constants of the æther should not be taken as mere numerics although their dimensional formulas are not defined. On the latter basi there is a dimensional difference of some kind between magnetic intensit in gilberts-per-centimeter and flux-density in gausses. The permeability ca also be expressed $\mu = 1 + 4\pi\kappa$ where κ is the **susceptibility.**

79. Names for the units in the C.G.S. magnetic and electric sub systems. Although the practical ohm-volt-ampere series of units is uni versally employed in the great majority of electrical applications, yet it i sometimes desirable to use the C.G.S. parent system of units and names fo such units have only been assigned authoritatively in a few instances, suc as the "dyne" for the unit of force, and the erg for the unit of work. It ha been suggested‡ that the C.G.S. magnetic units might be distinguished fro their prototypes in the practical system by the **prefix ab- or abs-** and als that the C.G.S. electrostatic units might be similarly distinguished by th **prefix abstat- or stat-**, as indicated in the following table, Par. **80.**

It should be borne in mind that the prefixes "ab" and "stat" have neve been authorized by any technical society or institution, and terms bearin these prefixes are therefore technically irregular. The excuse for this irregu larity is that no proper terms exist by which to describe these units, since th phrases "C.G.S. magnetic unit," or "C.G.S. electric unit," are cumbersom and insufficiently descriptive. Their merit is that there can be no ambiguit concerning the meaning of these irregular terms.

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* Maxwell, J. C. "A Treatise on Electricity and Magnetism." 1881 Vol. II, p. 244.

† Rücker. Phil. Mag., Feb., 1889.

‡ Trans. A. I. E. E., July, 1903, Vol. XXII, p. 529. Franklin, W. S "Electric Waves," New York, Macmillan Co., 1909, p. 67. Hering, C. "Con version Tables," New York, John Wiley & Sons, 1904. Pender, Harold "American Handbook for Electrical Engineers," New York, John Wiley & Sons, 1914.

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80. Table of relations between the practical and corresponding C.G.S. units

Quantity	Symbol	Practical unit	C.G.S. magnetic unit	C.G.S. electric unit
E.m.f.	E	volt $= 10^8$ abvolts volt $= 3.\dot{3} \times 10^{-3}$ statvolt	abvolt $= 10^{-8}$ volt abvolt $= 3.\dot{3} \times 10^{-11}$ statvolt	statvolt $= 300$ volts statvolt $= 3 \times 10^{10}$ abvolts
Resistance	R	ohm $= 10^9$ absohms ohm $= 1.\dot{1} \times 10^{-12}$ statohm	absohm $= 10^{-9}$ ohm absohm $= 1.\dot{1} \times 10^{-21}$ statohm	statohm $= 9 \times 10^{11}$ ohms statohm $= 9 \times 10^{20}$ absohms
Current	I	ampere $= 10^{-1}$ absampere ampere $= 3 \times 10^9$ statamperes	absampere $= 10$ amperes absampere $= 3 \times 10^{10}$ statampere	statampere $= 3.\dot{3} \times 10^{-10}$ ampere statampere $= 3.\dot{3} \times 10^{-11}$ absampere
Quantity	Q	coulomb $= 10^{-1}$ abcoulomb coulomb $= 3 \times 10^9$ statcoulombs	abcoulomb $= 10$ coulombs abcoulomb $= 3 \times 10^{10}$ statcoulomb	statcoulomb $= 3.\dot{3} \times 10^{-10}$ coulomb statcoulomb $= 3.\dot{3} \times 10^{-11}$ abcoulomb
Capacitance	C	farad $= 10^{-9}$ abfarad farad $= 9 \times 10^{11}$ statfarads	abfarad $= 10^9$ farads abfarad $= 9 \times 10^{20}$ statfarad	statfarad $= 1.\dot{1} \times 10^{-12}$ farad $= 1.\dot{1}$ $\mu\mu f$ statfarad $= 1.\dot{1} \times 10^{-21}$ abfarad
Inductance	L	henry $= 10^9$ abhenrys henry $= 1.\dot{1} \times 10^{-12}$ stathenry	abhenry $= 10^{-9}$ henry abhenry $= 1.\dot{1} \times 10^{-21}$ stathenry	stathenry $= 9 \times 10^{11}$ henrys stathenry $= 9 \times 10^{20}$ abhenrys
Energy	W	joule $= 10^7$ abjoules or ergs joule $= 10^7$ statjoules or ergs	abjoule or erg $= 10^{-7}$ joule abjoule or erg $= 1$ statjoule or erg	statjoule or erg $= 10^{-7}$ joule statjoule or erg $= 1$ abjoule or erg
Power	P	watt $= 10^7$ abwatts or $\frac{\text{ergs}}{\text{sec.}}$ watt $= 10^7$ statwatts " "	abwatt or $\frac{\text{erg}}{\text{sec.}} = 10^{-7}$ watt abwatt or $\frac{\text{erg}}{\text{sec.}} = 1$ statwatt	statwatt or $\frac{\text{erg}}{\text{sec.}} = 10^{-7}$ watt statwatt or $\frac{\text{erg}}{\text{sec.}} = 1$ abwatt

NOTE: A dot over a number indicates a recurring decimal.

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DEFINITIONS OF PHOTOMETRIC UNITS

81. Luminous flux (F), (light) is the physical stimulus produced by radiation, which excites vision. It is proportional to the rate of flow of radiant energy and to a **stimulus coefficient** which depends chiefly on the spectral distribution of that energy. The stimulus coefficient for radiation of a particular wave-length is the ratio of the luminous flux to the radiant power producing it. The conventional unit of luminous flux is the **lumen** or the flux emitted by **one international candle** through one **steradian.**

82. Luminous intensity (I), or candle-power. The luminous intensity of a point source of light is the solid-angular density of the luminous flux emitted by the source in the direction considered; or it is the flux per steradian in that direction. The conventional unit is the candle-power, or the (candle) lumen per steradian.

83. International candle. A standard of luminous intensity, conventionally equal to the **bougie decimal,** maintained between the national laboratories of England, France and America through the medium of groups of standard incandescent lamps seasoned and intercompared. The intensity given by this standard is the conventional unit or candle.

84. True specific luminous intensity (b_s) of an element of a luminous surface is the ratio of the luminous intensity of the element, taken normally, to the area of the element. The conventional unit is the **candle per square centimeter;** or the lumen per sq. cm.

85. Apparent specific luminous intensity, or brightness (b), of an element of a luminous surface, from a given position, is the luminous intensity per unit area of the surface projected on a plane perpendicular to the line of sight, and including only a surface of dimensions small in comparison with the distance from the observer. The conventional unit is the **candle per square centimeter of projected area;** or the apparent lumen per sq. cm. For luminous surfaces obeying Lambert's law, or the "cosine law," the true and the apparent specific luminous intensities are equal. In practice, the apparent specific intensity is ordinarily observed. It has been proposed to call a brightness of one apparent lumen per sq. cm. one "lambert."

86. Illumination on a surface (E) is the luminous flux-density over the surface, or the flux per unit of intercepting area. The practical unit is the **lumen per square foot** or the **foot-candle.** The conventional unit is the **lumen per square centimeter** which has been termed the **"phot"** by Blondel. It is a cm-candle. The meter-candle, or 10^{-4} phot, is sometimes called the candle-lux. The milliphot (10^{-3} phot = millilumen per square centimeter) is roughly equal to a foot-candle, since 1 foot-candle = 1.0764 milliphots. A perfectly diffusing surface having a reflection coefficient of unity, and illumined with 1 phot, would have a brightness of 1 lambert.

DEFINITIONS OF THERMAL UNITS

87. Temperature. The thermal condition of a body considered with reference to its capability to communicate heat to other bodies. Bodies at the same temperature do not communicate heat to one another at their bounding surfaces. The conventional unit is the **degree centigrade.** Other units in practical use are the degree **fahrenheit,** and occasionally the degree **réaumur.**

88. Quantity of heat. The amount of heat energy contained in a body or transferred from one body to another, by virtue of which temperatures are established or changed. Since heat is a form of energy, a quantity of heat may be expressed in units of energy of any kind. Two types of units are employed, one thermal, the other dynamical. As thermal units the C.G.S. unit is the **"lesser-calorie"** or **"therm"** or **"water-gram-degree centigrade,"** *i.e.*, the quantity of heat required to raise 1 g. of water 1 deg. cent.; and as this differs slightly with the temperature, the interval from 15 deg. to 16 deg. cent. is given in the definition. A larger decimal multiple of this unit, called the **"greater calorie"** or **"kilogram-calorie"** is much used and is equal to 1,000 lesser calories. A practical unit is the **"British thermal unit"** (B.t.u.), or the heat required to raise 1 lb. of water 1 deg. fahr. Dynamic units are the erg, the joule, the watt-hr., etc.

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88. Specific heat is the ratio of the quantity of heat required to raise unit mass of the substance through unit difference of temperature, to that required to raise unit mass of water the same interval. In the C.G.S. thermal system this is numerically the same as the quantity of heat required to raise 1 g. of the substance 1 deg. cent. at the temperature considered. The unit is a mere numeric in any system.

90. Thermal conductivity. A specific thermal conducting power. It is numerically equal to the flow of heat occurring through a 1-cm. slab of the material, through a cross-sectional area of 1 sq. cm., when the difference of temperature between the surfaces of the slab is 1 deg. cent. The C.G.S. dynamical unit is the abwatt per centimeter and per degree centigrade.

91. Thermal resistance. Opposition to the flow of heat by conduction. Unit thermal resistance in a heat conductor permits unit flow of heat under unit difference of temperature. If the flow of heat is measured in abwatts or ergs per second, and the difference of temperature is in deg. cent., the unit has been called the thermal absohm. If the flow of heat is measured in watts, the unit has been called the thermal ohm.

92. Thermal resistivity. The reciprocal of thermal conductivity, and measurable in thermal ohm-cm. or absohm-cm.

93. Latent heat. The quantity of heat required to change the physical state of unit mass of a substance without changing its temperature, as for instance to convert 1 g. of water at 100 deg. cent. into saturated dry steam at 100 deg. cent. The dynamical C.G.S. unit is the erg per gram.

94. Entropy. A quantitative property of a body which is constant when the quantity of heat contained in it is constant; but which increases or decreases as the body gains or loses heat. In any small change of the quantity of heat contained in the body, the change in entropy is the ratio of the change in quantity of heat to the absolute temperature at which the change took place. The C.G.S. unit is the erg per degree absolute.

96. Coefficient of expansion, at any temperature, is the ratio of the change in dimensions of a body to the original dimensions, per degree centigrade of temperature increase. The expansion may be linear, as in the case of a metallic wire; or it may be voluminal as in the case of a fluid. In either case the unit is a numeric divided by a change of temperature.

96. Emissivity. The rate of emission of heat from a body per unit of surface area and per degree centigrade elevation of temperature above its surroundings. The C.G.S. dynamical unit is the erg per second, per square centimeter and per degree centigrade.

97. Mechanical equivalent of heat. The value in mechanical units of energy corresponding to a given quantity of heat; and, in particular, the value in mechanical units corresponding to a unit quantity of heat such as a lesser calorie, a thermie or a B.t.u.

DIMENSIONAL FORMULAS

98. Each and every derived unit in an absolute system is necessarily formed from the fundamental units of that system in one and only one combination. The particular combination of fundamental units entering into a derived unit expresses its **dimensions,** and when presented algebraically, is called the **dimensional formula** of the unit. Any statical or dynamical unit in a kinetic absolute system involves only three fundamental units, or has dimensions in three fundamental units. Electric or magnetic units involve five fundamental units.

99. As a simple example, we may consider the unit of velocity. A velocity is necessarily a length divided by a time. The notion of mass is not involved in the concept of velocity. Consequently, if we denote the units of length, mass and time by L, M, and T, respectively, the nature of unit velocity V is expressed by the formula

$$V = L/T = LT^{-1} \qquad \text{(velocity unit)} \qquad (9)$$

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The dimensions of velocity are therefore LT^{-1}, or the first positive power o length and the first negative power of time. Since mass does not appear i this dimensional formula we may write the formal dimensions of velocity a $L^1M^0T^{-1}$. The three exponents 1, 0 and −1 completely define the nature o velocity in any absolute system whose fundamental units are length, mas and time. Moreover, the dimensional formula of a unit assigns at once th size of a unit when systems employing different fundamental units ar compared. Thus if we should compare the unit of velocity in the C.G.S. sys tem with that, say, in the meter-kilogram-day system; then in the latte the unit would be the meter per day while in the former it would be th centimeter per second.

100. Taking the more complex case of the magnetic unit of, say current-density in a system whose fundamental units are those of both th practical and C.G.S. systems; namely, length, mass, time, magnetic æthe constant μ, and dielectric æther constant k. Then the dimensional formul of current-density is $L^{-\frac{3}{2}}M^{\frac{1}{2}}T^{-1}\mu^{-\frac{1}{2}}$. If now we compare the size of the prac tical unit with that of the C.G.S. unit the former has a unit length of a quad rant or 10^9 cm., and a mass unit of 10^{-11} g. Consequently, the size of th practical unit is to the size of the C.G.S. unit in the ratio $(10^9)^{-\frac{3}{2}} \times (10^{-11})^{\frac{1}{2}} = 10^{-16}$; so that the practical unit, the ampere per square quadrant, is les than the C.G.S. unit or absampere per square centimeter in the ratio 10^{-1} For practical purposes, we should probably ignore the systematic practica unit of current density, the ampere per square quadrant, and select a hybri unit, say the ampere per square centimeter or per square inch. By such departure from the absolute system, however, the fundamental equation of the system involving lengths, areas, or volumes, may become erroneou unless we introduce compensating numerical coefficients.

100a. Vector units and complex quantities. As is explained in Sec 2, at Par. 163 and elsewhere, vector alternating quantities are much use in electrical engineering, and call for corresponding vector units, as well a vector symbols, in the formulas relating to such quantities. Strictly speak ing, such quantities and units are not vectors in the mathematical sense o that term, but are "complex" quantities and units, because when two suc quantities are multiplied together, they do not possess both a "vector prod uct" and a "scalar product" as is the case when two mathematical vector are multiplied. Nevertheless, such alternating quantities may be calle "plane vectors" to avoid conflict with mathematical usage, and the wor "vector," which is much used in alternating-current literature, may then b interpreted, in this sense, as subject to the algebra of complex quantities in plane.

It is not only logical but also very desirable to distinguish between simpl and complex quantities, *i.e.*, between scalars and vectors in alternating-cur rent formulas employing both. There are three ways in which this is done

1. Distinctive symbols, or types of symbol, are used to designate vectors Thus a scalar e.m.f. in volts might be represented by E and a vector by $\mathbf{E}$ o $\mathfrak{E}$, *i.e.*, by a black letter capital, or by a gothic capital, of the same letter This method has the disadvantage of calling for and reserving special font in representing vectors.

2. The same symbol may be used, but a distinctive mark, such as a "under dot," may be applied to symbols representing vector quantities. Thus a scalar e.m.f. in volts might be represented by E, and a vector e.m.f. by $\dot{E}$. In any formula or equation, if any one term is a vector, all of its terms must be vectors; so that the under dot must be applied to each and every term of a vector equation. This method has the disadvantages that it is difficult to print or to set up in type, and that a page containing many vector formulas presents a speckled appearance.

3. No special symbols or symbol marks may be used for vector quantities, but the unit at the end of the line on which the equation appears may have a distinctive sign, such as an angle mark ($\angle$), to indicate that the equation employs vectors. Thus the equation

$$E = IZ_1 + IZ_2 + IZ_3 \quad \text{volts} \angle$$

would indicate that the e.m.f. E is a vector, and can be represented by the polygonal or vector sum of three vector elements. In this case the unit of the equation becomes a "vector volt."

101. The international metric system. There are only three units

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in the metric system—the meter, the gram and the liter, with decimal derivatives denoted by prefixes common to all parts of the system, including all C.G.S. units and electric or magnetic units.

102. The Metric Prefixes

Greek roots	Mega-	= 1,000,000	$= 10^6$	Greek for great
	Myria-	= 10,000	$= 10^4$	Greek for 10,000 as in word myriad
	Kilo-	= 1,000	$= 10^3$	Greek for 1,000
	Hecto-	= 100	$= 10^2$	Greek for 100
	Deka-	= 01	$= 10^1$	Greek for 10
Latin roots	Deci-	= 1/10	$= 10^{-1} = \frac{1}{10}$	= Latin for 10 as in U. S. dime
	Centi-	= 1/100	$= 10^{-2} = \frac{1}{100}$	= Latin for 100 as in U. S. cent
	Milli-	= 1/1000	$= 10^{-3} = \frac{1}{1000}$	= Latin for 1,000 as in U. S. mill

Greek Micro- = 1/1,000,000 = 10^{-6} = Greek for small

Millimicro is used for 10^{-9} and micromicro for 10^{-12}.

103. Examples of use of prefixes. The length of 1 statute English mile is expressed in the metric system as 1609.33 meters or 1609.33 m. This may also be expressed as: 1.60933 kilometers or 1.60933 km.

or 16.0933 hectometers	or 160933 centimeters
" 160.933 dekameters	" 1609330 millimeters
" 16093.3 decimeters	" 1.60933×10^9 microns

The prefix may be regarded either as designating a secondary unit decimally related to the primary unit, or as indicating a change in the decimal point of the number expressing the dimensions, without changing the unit. Just as the unit of American currency, the dollar, may be expressed either as 1 dollar, 10 dimes, 100 cents, or 1,000 mills, so each of the terms dime, cent, and mill may be regarded either as defining a secondary unit decimally related to the dollar; or as changing the place of the decimal in expressing a sum of money, without departing from the dollar unit; since \$10.93 = 109.3 dimes = 1093 cents = 10,930 mills.

104. Fig. 3 shows to scale, a length of 1 decimeter, or about one hand's breadth. This is one-tenth of a meter. It is divided into 10 parts, each 1/100th of a meter or 1 centimeter. Each centimeter is again divided into 10 parts, each 1/1000th of a meter or 1 millimeter.

105. If a cube is formed of decimeter edges, the volume of the cube is a cubic decimeter, and is called a **liter.** It is about midway between a dry U. S. quart and a liquid U. S. quart; so that a liter may be regarded for rough purposes as a quart. One cubic centimeter of water weighs 1 g. So that a liter of water weighs 1,000 g. or a kilogram, which is roughly 2 lb. avoirdupois (2.205 lb.)

106. Metric length. 1 meter = 39.37 U. S. inches or roughly a yard or exactly 3 ft. 3 in. + $\frac{3}{8}$ in. + $\frac{7}{10}$ in. + $\frac{3}{100}$ in. Common decimal derivatives are the kilometer (km.) of roughly $\frac{5}{8}$ statute mile; the centimeter (cm.) roughly $\frac{2}{5}$ inch; the millimeter (mm.) roughly $\frac{1}{25}$ inch.

107. Metric area. 1 sq. m. = 1.196 sq. yd. or roughly a square yard, and decimal derivatives, such as the square centimeter, or square millimeter. In land measure, a square dekameter or an area 10 m. by 10 m. = 100 sq. m. is called an ar. A square 100 m. by 100 m. = 10,000 sq. m., contains 100 ars or is 1 hectar and forms the metric acre. 1 hectar = 2.471 acres. The square kilometer contains just 100 hectars.

108. Metric volume. 1 cu. m., sometimes called a stere, = 1.308 cu. yd. or roughly 1$\frac{1}{3}$ cu. yd.

109. Metric mass. 1 g. the mass of 1 cu. cm. of water. Common decimal derivatives are the kilogram, or the mass of 1 liter of water; the megagram, or **metric ton,** the mass of 1 cu. m. of water. The metric ton (1,000 kg.) is a little less than the long ton (0.984) so that for many purposes it may be taken as a long ton.

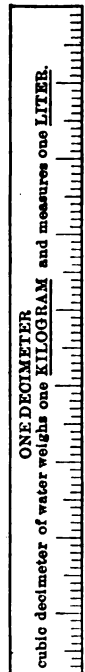


FIG. 3.

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TABULAR SUMMARY OF DEFINITIONS OF UNITS

110. Fundamental Units

Symbol	Quantity	Equation	Dimension	C.G.S. units	Abbreviation	Practical units, English	Abbreviation	Value in C.G.S.
L	Length	———	L	Centimetre	cm.	Foot Inch	ft. in.	30.48 2.54
M	Mass	———	M	Gram	g.	Pound	lb.	453.59
T	Time	———	T	Second	sec.	Minute Second	min. sec.	60. 1.

111. Auxiliary Fundamental Units

μ	Magnetic permeability	———	μ					
k	Electric permeability	———	k					
θ	Temperature	———	θ					

112. Geometrical Units

A	Area	$A = L_1 L_2$	L^2	Square centimeter	sq. cm.	Square foot Square inch	sq. ft. sq. in.	929.03 6.45
V	Volume	$V = L_1 L_2 L_3$	L^3	Cubic centimeter	cu. m. cu. cm.	Cubic foot Cubic inch	cu. ft. cu. in.	28,317. 16.39
α β	Plane angle	$\alpha = \frac{jL_1}{L_2}$	j number	Radian { Degree Minute Second	{ Deg. Min. Sec.	{ Degree Minute Second	{ Deg. Min. Sec.	
ψ	Solid angle	$\psi = A/L^2$	number					

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118. Mechanical Units

δ	Density	$\delta = \frac{M}{V}$	$M L^{-3}$	Grams per cubic centimeter	g. per cu. cm.	Pounds per cubic foot	lb. per cu. ft.	1.602×10^{-2}
	Specific gravity	$\frac{\delta}{\delta}$	number					
v	Velocity linear	$v = \frac{d L}{d T}$	$L T^{-1}$	Centimeters per second	cm. per sec.	Feet per minute Feet per second	ft. per min. ft. per sec.	0.508 30.48
ω	Angular Velocity	$\omega = \frac{d \alpha}{d T}$	$j T^{-1}$	Radians per second	rad. per sec.	Revolutions per minute	r.p.m.	
a	Acceleration	$a = \frac{d v}{d T}$	$L T^{-2}$	Centimeters per second per second	cm. per sec. per sec.	Miles per hour per second Feet per second per second	miles per hr. per sec. ft. per sec. per sec.	44.70 30.48
	Acceleration angular	$\frac{\omega}{T}$	$j T^{-2}$	Radians per second per second	rad. per sec. per sec.			
	Momentum	$M v$	$L M T^{-1}$	Gram-centimeter per second	gm.-cm. per sec.	Foot-pound per minute	ft-lb. per min.	230.4
	Moment of momentum	$M v L$	$L^2 M T^{-1}$	Gram-centimeter squared per second	gm.-cm.^{2} per sec.			

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Symbol	Quantity	Equation	Dimension	C.G.S. units	Abbreviation	Practical units English	Abbreviation	Value in C.G.S.
F	Force	$F = M\,a$	$L\,M\,T^{-2}$	Dyne		Pound (av.) weight	lb.	4.448×10^5
	Force intensity	$\frac{F}{M}$	$L\,T^{-2}$	Dyne per gram				
g	Gravitation constant	$g = \frac{F}{M}$	$L\,T^{-2}$	cm. per sec. per sec.		Foot per sec. per sec.	ft. per sec.^{2}	30.48
	Force of a centre of attraction	$\frac{F}{L^2\,M}$	$L^{-1}\,T^{-2}$					
	Surface tension	$\frac{F}{L}$	$M\,T^{-2}$	Dyne per centimeter	dyne per cm.			
p	Intensity of pressure	$p = \frac{F}{A}$	$L^{-1}\,M\,T^{-2}$	Dyne per square centimeter or bar	Bar	Pound per square inch	lb. per sq. in	6.894×10^4
	Modulus of elasticity	$\frac{F}{A}$	$L^{-1}\,M\,T^{-2}$	Dyne per square centimeter	dyne per sq. cm.	Pound per square inch		
T	Torque	$T = \frac{W}{\alpha}$	$-j\,L^2\,M\,T^{-2}$	Dyne-perp.-centimeter	dyne-perp.-cm.	Pound-perp.-foot	lb-perp.-ft.	1.356×10^7
	Directive force	$\frac{T}{\alpha}$	$L^2\,M\,T^{-2}$	Dyne-perp. cm. per radian or degree				

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Mechanical Units.—*Concluded*

J	Moment of inertia	$\int L^2 \, d \, M$	$L^2 \, M$	Gram-centimeter^2	gm. cm.^{2}			
K	Radius of gyration	$\sqrt{\frac{I}{M}}$	L	Centimeter	cm.	Foot, inch		
W	Energy	$W = F \, L$	$L^2 \, M \, T^{-2}$	Erg	spell out	Foot-pound	ft-lb.	1.356×10^7
W	Vis Viva	$W = \frac{M \, v^2}{2}$	$L^2 \, M \, T^{-2}$	Erg	spell out			1.356×10^7
W	Impact	$W = \frac{M \, v^2}{2}$	$L^2 \, M \, T^{-2}$	Erg	spell out			1.356×10^7
	Resilience	$\frac{W}{V}$	$L^{-1} \, M \, T^{-2}$	Erg per cubic centimeter	Erg per c.c.	Foot-pound per cubic inch		
P	Power	$P = \frac{d \, W}{d \, T}$	$L^2 \, M \, T^{-3}$	Erg per second	erg per sec.	Watt	w.	10^7
η	Efficiency	$\eta = \frac{P_2}{P_1}$	number					

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114. Magnetic Units

Symbol	Quantity	Equation	Dimensional formula		C.G.S. units	Abbreviations
			Electromagnetic	Electrostatic		
m	Pole strength	$m = \sqrt{F L^2 \mu}$	$L^{\frac{3}{2}} M^{\frac{1}{2}} T^{-1} \mu^{\frac{1}{2}}$	$L^{\frac{1}{2}} M^{\frac{1}{2}} k^{-\frac{1}{2}}$		
$\mathfrak{M}$	Magnetic moment	$\mathfrak{M} = m L$	$L^{\frac{5}{2}} M^{\frac{1}{2}} T^{-1} \mu^{\frac{1}{2}}$	$L^{\frac{3}{2}} M^{\frac{1}{2}} k^{-\frac{1}{2}}$		
$\mathcal{H}$	Field intensity	$\mathcal{H} = \frac{\mathcal{F}}{L}$	$L^{-\frac{1}{2}} M^{\frac{1}{2}} T^{-1} \mu^{-\frac{1}{2}}$	$L^{\frac{1}{2}} M^{\frac{1}{2}} T^{-2} k^{\frac{1}{2}}$	Gilbert per cm.	
$\mathfrak{I}$	Intensity of magnetization	$\mathfrak{I} = \frac{\mathfrak{M}}{V}$	$L^{-\frac{1}{2}} M^{\frac{1}{2}} T^{-1} \mu^{\frac{1}{2}}$	$L^{-\frac{3}{2}} M^{\frac{1}{2}} k^{-\frac{1}{2}}$		
ϕ	Flux	$\phi = \mu \mathcal{H} A$	$L^{\frac{3}{2}} M^{\frac{1}{2}} T^{-1} \mu^{\frac{1}{2}}$	$L^{\frac{1}{2}} M^{\frac{1}{2}} k^{-\frac{1}{2}}$	Maxwell	
$\mathfrak{B}$	Flux density	$\mathfrak{B} = \frac{\phi}{A}$	$L^{-\frac{1}{2}} M^{\frac{1}{2}} T^{-1} \mu^{\frac{1}{2}}$	$L^{-\frac{3}{2}} M^{\frac{1}{2}} k^{-\frac{1}{2}}$	Gauss	
$\mathcal{H}$	Magnetizing force	$\mathcal{H} = \frac{4\pi N I}{L}$	$L^{-\frac{1}{2}} M^{\frac{1}{2}} T^{-1} \mu^{-\frac{1}{2}}$	$L^{\frac{1}{2}} M^{\frac{1}{2}} T^{-2} k^{\frac{1}{2}}$	Gilbert per cm.	
$\mathcal{F}$	Magnetomotive force	$\mathcal{F} = 4\pi N I$	$L^{\frac{1}{2}} M^{\frac{1}{2}} T^{-1} \mu^{-\frac{1}{2}}$	$L^{\frac{3}{2}} M^{\frac{1}{2}} T^{-2} k^{\frac{1}{2}}$	Gilbert	
ν	Reluctivity	$\nu = \frac{1}{\mu}$	μ^{-1}	$L^2 T^{-2} k$	Oersted-centimeter	

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Magnetic Units.—*Concluded*

$\mathfrak{R}$	Reluctance	$\mathfrak{R} = \nu \frac{L}{A} = \frac{\mathfrak{F}}{\phi}$	$L^{-1}\mu^{-1}$	$L\,T^{-2}\,k$	Oersted	
μ	Permeability	$\mu = \frac{\mathfrak{G}}{\mathfrak{H}}$	μ	$L^{-2}\,T^{2}\,k^{-1}$		
$\mathcal{P}$	Permeance	$\mathcal{P} = \frac{1}{\mathfrak{R}}$	$L\,\mu$	$L^{-1}\,T^{2}\,k^{-1}$		
κ	Susceptibility	$\kappa = \frac{\mathfrak{I}}{\mathfrak{H}}$	μ	$L^{-2}\,T^{2}\,k^{-1}$		
W	Magnetic energy	$W = \mathfrak{F}\,\phi$	$L^{2}\,M\,T^{-2}$	$L^{2}\,M\,T^{-2}$	Erg	
	Magnetic potential	$\frac{W}{m}$	$L^{\frac{1}{2}}\,M^{\frac{1}{2}}\,T^{-1}\,\mu^{-\frac{1}{2}}$	$L^{\frac{3}{2}}\,M^{\frac{1}{2}}\,T^{-2}\,k^{\frac{1}{2}}$		
P	Magnetic power	$P = F\,\phi/T$	$L^{2}\,M\,T^{-3}$	$L^{2}\,M\,T^{-3}$	Erg per sec.	

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Symbo	Quantity	Equation	Dimensional formula		Practical units	Abbreviations	Value of practical units in electromagnetic units
			Electromagnetic	Electrostatic			
I, i	Current	$I = \frac{E}{Z}$ $I = \frac{Q}{T}$	$L^{\frac{1}{2}} M^{\frac{1}{2}} T^{-1} \mu^{-\frac{1}{2}}$	$L^{\frac{3}{2}} M^{\frac{1}{2}} T^{-2} k^{\frac{1}{2}}$	Ampere	amp.	10^{-1}
	Current density	$\frac{I}{A}$	$L^{-\frac{3}{2}} M^{\frac{1}{2}} T^{-1} \mu^{-\frac{1}{2}}$	$L^{-\frac{1}{2}} M^{\frac{1}{2}} T^{-2} k^{\frac{1}{2}}$	Ampere per square centimeter	amp. per sq. cm.	10^{-1}
Q, q	Quantity	$Q = I\,T$	$L^{\frac{1}{2}} M^{\frac{1}{2}} \mu^{-\frac{1}{2}}$	$L^{\frac{3}{2}} M^{\frac{1}{2}} T^{-1} k^{\frac{1}{2}}$	Coulomb Ampere-hour	spell out amp-hr.	10^{-1} 360
R, r	Resistance	$R = \frac{P}{I^2}$	$L\,T^{-1}\,\mu$	$L^{-1}\,T\,k^{-1}$	Ohm	spell out	10^{9}
E, e	Electromotive force	$E = \frac{d}{d}\frac{\phi}{T}$ $E = \frac{W}{Q}$	$L^{\frac{3}{2}} M^{\frac{1}{2}} T^{-2} \mu^{\frac{1}{2}}$	$L^{\frac{1}{2}} M^{\frac{1}{2}} T^{-1} k^{-\frac{1}{2}}$	Volt	spell out	10^{8}
ρ_m	Mass resistivity	$\rho_m = \frac{R}{L} \cdot \frac{M}{L}$	$L^{-1} M^{1} T^{-1} \mu$	$L^{-2} MT\,k^{-1}$	Ohm (gm. meter)	meter-gm.	
ρ_v	Volume resistivity	$\rho_v = \frac{RA}{L}$	$L^{2}\,T^{-1}\,\mu$	$T\,k^{-1}$	Ohm-centimeter	ohm-cm.	10^{9}

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Electric Units.—Continued

C	Capacitance	$C = \frac{Q}{E}$	$L^{-1} T^2 \mu^{-1}$	$L\,k$	Farad Microfarad	spell out mf.	10^{-9} 10^{-15}
G, g	Conductance	$G = \frac{R}{Z^2}$	$L^{-1} T \mu^{-1}$	$L\,T^{-1} k$	Mho	spell out	10^{-9}
B, b	Susceptance	$B = \frac{X}{Z^2}$	$L^{-1} T \mu^{-1}$	$L\,T^{-1} k$	Mho.	spell out	10^{-9}
Y, y	Admittance	$Y = \sqrt{G^2 + B^2} = \frac{1}{Z}$	$L^{-1} T \mu^{-1}$	$L\,T^{-1} k$	Mho	spell out	10^{-9}
γ	Conductivity	$\gamma = \frac{1}{\rho}$	$L^{-2} T \mu^{-1}$	$T^{-1} k$	Mho per centimetre	mho per cm.	10^{-9}
τ	Time constant	$\frac{L}{R}$	T	T	Second	sec.	1
T	Period or cycle	$T = \frac{1}{f}$	T	T	Second	sec.	1
f	Frequency	$f = \frac{1}{T}$	T^{-1}	T^{-1}	Cycles per second	cycles per sec.	1
ω	Angular velocity	$\omega = 2\pi f$	T^{-1}	T^{-1}			

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Electric Units.—*Continued*

Symbol	Quantity	Equation	Dimensional formula		Practical Units	Abbreviations	Value of practical units in electromagnetic units
			Electromagnetic	Electrostatic			
	Electro-kinetic momentum	$I\,L$	$L^{\frac{3}{2}}\,M^{\frac{1}{2}}\,T^{-1}\,\mu^{\frac{1}{2}}$	$L^{\frac{1}{2}}\,M^{\frac{1}{2}}\,k^{-\frac{1}{2}}$			
	Thermoelectric height or specific heat of electricity	$\frac{E^{**}}{\theta}$	$L^{\frac{3}{2}}M^{\frac{1}{2}}\,T^{-2}\,\theta^{-1}\mu^{\frac{1}{2}}$	$L^{\frac{1}{2}}\,M^{\frac{1}{2}}\,T^{-1}\,\theta^{-1}\,k^{-\frac{1}{2}}$			
	Coefficient of Peltier effect	$\frac{H}{I\,T}$†	$L^{-1}\,M^{\frac{1}{2}}\,\theta\,\mu^{\frac{1}{2}}$	$L^{-\frac{3}{2}}\,M^{\frac{1}{2}}\,T\,\theta\,k^{-\frac{1}{2}}$			
	Coefficient of Peltier effect	$\frac{W}{I\,T}$	$L^{\frac{3}{2}}\,M^{\frac{1}{2}}\,T^{-2}\,\mu^{\frac{1}{2}}$	$L^{\frac{1}{2}}\,M^{\frac{1}{2}}\,T^{-1}\,k^{-\frac{1}{2}}$			
	Surface density	$\frac{Q}{A}$	$L^{-\frac{3}{2}}\,M^{\frac{1}{2}}\,\mu^{-\frac{1}{2}}$	$L^{-\frac{1}{2}}\,M^{\frac{1}{2}}\,T^{-1}\,k^{\frac{1}{2}}$	Coulomb per square centimetre	coulomb per sq. cm.	
L	Coefficient of self induction	$L=\frac{N\,\phi}{I}$	$L\,\mu$	$L^{-1}\,T^{2}\,k^{-1}$	Henry	spell out	10^{9}
X_s	Inductive reactance	$X_s=2\,\pi\,f\,L$	$L\,T^{-1}\,\mu$	$L^{-1}\,T\,k^{-1}$	Ohm	spell out	10^{9}

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X_c	Condensive reactance	$X_c = \frac{1}{2\pi f C}$	$L\,T^{-1}\,\mu$	$L^{-1}\,T\,k^{-1}$	Ohm	spell out	10^9
X, x	Reactance	$X = X_s - X_c$	$L\,T^{-1}\,\mu$	$L^{-1}\,T\,k^{-1}$	Ohm	spell out	10^9
Z, z	Impedance	$Z = \sqrt{R^2 + X^2}$	$L\,T^{-1}\,\mu$	$L^{-1}\,T\,k^{-1}$	Ohm	spell out	10^9
P	Electric power	$P = E\,I$	$L^2\,M\,T^{-3}$	$L^2\,M\,T^{-3}$	Watt	spell out	10^7
W	Electric energy	$W = P\,T$	$L^2\,M\,T^{-2}$	$L^2\,M\,T^{-2}$	Joule watt-hour	spell out watt-hr.	10^7 3.6×10^{10}
	Power-factor	$\frac{\text{active } P}{\text{apparent } P}$	number	number			
	Reactive factor	$\frac{\text{reactive } P}{\text{apparent } P}$	number	number			
	116. Electrochemical Units						
	Ionic charge	$\frac{Q}{M}$	$L^{\frac{1}{2}}\,M^{-\frac{1}{2}}\,\mu^{-\frac{1}{2}}$	$L^{\frac{3}{2}}\,M^{-\frac{1}{2}}\,T^{-1}\,k^{\frac{1}{2}}$	Coulomb per univalent gram-ion	spell out	
	Electrochemical equivalent	$\frac{M}{Q}$	$L^{-\frac{1}{2}}\,M^{\frac{1}{2}}\,\mu^{\frac{1}{2}}$	$L^{-\frac{3}{2}}\,M^{\frac{1}{2}}\,T\,k^{-\frac{1}{2}}$	Gram per coulomb	spell out	
	Electric deposition	$\frac{M}{T}$	$M\,T^{-1}$	$M\,T^{-1}$	Gram per second	g. per sec.	

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117. Photometric Units ††

Symbol	Quantity	Equation	Dimensional formula	Unit	Abbreviation	
Q	Quantity of light	$Q = \phi T$	$L^2 M T^{-3}$	Lumen-hour		
ϕ	Flux of light	$\phi = \frac{Q}{T}$	$L^2 M T^{-3}$	Lumen		
I	Intensity of light	$I = \frac{\phi}{\text{solid angle}}$	$L^2 M T^{-3}$	Candle		
b	Brightness	$b = \frac{I}{A}$	$M T^{-3}$	Candle or lumen per square centimeter	c. per sq. cm.	
E	Illumination	$\frac{\phi}{A}$	$M T^{-3}$	Phot, Foot-candle, Lux		

118. Thermal Units ††

Symbol	Quantity	Equation	Dimensional Formulas‡			
			Dynamical	Thermal	Thermometric	$\theta = H + M$
H	Heat	$H = W$ $H = M\theta$ $H = V\theta$	$L^2 M T^{-2}$	$M\theta$	$L^2\theta$	$L^2 M T^{-2}$
	Rate of heat production	$\frac{H}{T}$	$L^2 M T^{-3}$	$M T^{-1}\theta$	$L^2 T^{-1}\theta$	$L^2 M T^{-3}$

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Thermal Units —*Concluded* ††

θ	Temperature		θ	θ	θ	$L^2\,T^{-2}$†††
	Coefficient of expansion	$\frac{V - V_1}{V\,(\theta - \theta_1)}$	θ^{-1}	θ^{-1}	θ^{-1}	$L^{-2}\,T^2$
	Entropy	$\frac{H}{\theta}$	$L^2\,M\,T^{-2}\,\theta^{-1}$	M	L^3	M
	Latent heat	$\frac{H}{M}$	$L^2\,T^{-2}$	θ	$L^3\,M^{-1}\,\theta$	$L^2\,T^{-2}$
	Conductivity	$\frac{H\,L}{T\,L^2\,\theta}$	$L\,M\,T^{-3}\,\theta^{-1}$	$L^{-1}\,M\,T^{-1}$	$L^2\,T^{-1}$	$L^{-1}\,M\,T^{-1}$
	Emissivity or immissivity	$\frac{H}{T\,L^2\,\theta}$	$M\,T^{-3}\,\theta^{-1}$	$L^{-2}\,M\,T^{-1}$	$L\,T^{-1}$	$L^{-2}\,M\,T^{-1}$
	Specific heat	$\frac{H}{H}$	number	number	number	number
	Capacity	$M \times$ sp. heat	M	M	M	M
J	Mechanical equivalent	$\frac{\text{mech. energy}}{\text{heat energy}}$	number	$L^2\,T^{-2}\,\theta^{-1}$	$L^{-1}\,M\,T^{-2}\,\theta^{-1}$	number

* N = number of turns. ** θ = temperature. † H = heat. †† Dimensional formulas deduced by Carl Hering. ‡ Taken from Carl Hering's "Conversion Tables." ‡‡ By assuming the dimensional formula of θ to be $L^2\,T^{-2}$, the dynamical and thermal formulas become identical; they are given in the last column.

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WEIGHTS AND MEASURES

NOTE:—In this and the following tables, the numerical values are not carried to more than four significant digits, a degree of precision sufficient for ordinary engineering purposes. For higher degrees of precision in conversion factors, reference may be made to publications of the Bureau of Standards, and to Hering's "Conversion Tables."

119. Linear Measure*

English*	U. S.	Abreviation	Metric equivalent	
			Meter	Reciprocal
	1 mil		0.000 0254	39,370
1 inch	1000 mils = 1 inch	in.	0.0254	39.37
4 inches = 1 hand			0.1016	9.843
7.92 inches = 1 surveyor's link	7.92 inches = 1 surveyor's link		0.2012	4.970
12 inches = 1 engineer's link = 1 foot	12 inches = 1 engineer's link = 1 foot	ft.	0.3048	3.281
3 feet = 1 yard	3 feet = 1 yard	yd.	0.9144	1.094
2 yards = 1 fathom	2 yards = 1 fathom		1.829	0.5468
5½ yards = 1 rod, pole, or perch	5½ yards = 1 rod, pole, or perch		5.029	0.1988
100 surveyor's links = 1 surveyor's chain = 66 feet.	100 surveyor's links = 1 surveyor's chain = 66 feet.	ch.	20.12	0.04970
100 engineer's links = 1 engineer's chain = 100 feet.	100 engineer's links = 1 engineer's chain = 100 feet.	ch.	30.48	0.03281
40 yards = 1 bolt (cloth)			36.58	0.02734
10 surveyor's chains = 1 furlong	40 rods = 1 furlong		201.2	0.004970
8 furlongs = 1 Statute mile	8 furlongs = 1 mile = 5280 feet		1,609	0.000 6214
1.152 statute mile = 1 nautical mile = 1 naut.	1.152 statute miles = 1 nautical mile = 6080 feet. = 1 naut.		1,853	0.000 5397
3 statute miles = 1 league			4,827	0.000 2071
60 nautical miles = 1 degree†	60 nautical miles = 1 degree†	deg.	111,100	0.9×10^{-5}

* Strictly speaking, there is a small difference between the English and United States inch, foot, yard, etc.; see Hering's "Conversion Tables;" but it is inappreciable for most engineering purposes. The units in the columns marked "English" are taken from Wightman's Arithmetical Tables, London, Old Westminster Press. The units in the columns marked "U. S." are taken from "The World Almanac," N. Y.

† 1 deg. of longitude on the equator is equal, more nearly to 60.07 nautical or 67.17 statute miles (111,300 m.).

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120. Square Measure

English	U. S.	Abbreviation	Metric equivalent	
			Square meters	Reciprocal
	1 circular mil = 0.7854 square mil		5.067×10^{-10}	1.974×10^{9}
	1 square mil		6.452×10^{-10}	1.550×10^{9}
	1 circular inch = 1,000,000 circular mils = 0.7854 square inch.		0.000 5067	1.974×10^{3}
1 square inch	1,000,000 square mils = 1 square inch	sq. in.	0.000 6452	1,550
144 square inches = 1 square foot	144 square inches = 1 square foot	sq. ft.	0.09290	10.76
9 square feet = 1 square yard	9 square feet = 1 square yard		0.8361	1.196
$30\frac{1}{4}$ square yards = 1 square rod or perch	$30\frac{1}{4}$ square yards = 1 square rod or perch		25.29	0.03954
40 square rods = 1 rood			1,012	0.0009881
4 roods = 1 acre	160 square rods = 1 acre		4,047	0.0002471
640 acres = 1 square mile	640 acres = 1 square mile		2.590×10^{6}	3.861×10^{-7}

121. Surveyor's Measure

English	U. S.	Metric equivalent	
		Square meters	Reciprocal
1 square surveyor's link	1 square surveyor's link	0.04047	24.71
625 square links = 1 square surveyor's pole	625 square links = 1 square surveyor's pole	25.29	0.03954
16 square poles = 1 square chain	16 square poles = 1 square surveyor's chain	404.7	0.002471
10 square surveyor's chains = 1 acre	10 square surveyor's chains = 1 acre	4,047	0.0002471
	40 acres = 1 forty	1.619×10^{5}	0.6177×10^{-5}
	4 forties = 1 quarter section	6.475×10^{6}	0.1544×10^{-6}
640 acres = 1 square mile	4 quarter sections = 1 square mile or section	2.590×10^{6}	0.3861×10^{-6}
	36 sections = 1 township	9.324×10^{7}	0.1073×10^{-7}

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122. Dry Measure (volume)

English	U. S.	Abbreviation	Metric equivalent	
			Liters*	Reciprocal
	1 pint	pt.	0.5506	1.816
1 pint		pt.	0.5682	1.760
	2 pints = 1 quart	qt.	1.101	0.9081
2 pints = 1 quart		qt.	1.136	0.8799
4 quarts = 1 gallon		gal.	4.546	0.2200
	8 quarts = 1 peck		8.810	0.1135
2 gallons = 1 peck			9.092	0.1100
	4 pecks = 1 bushel		35.24	0.02838
4 pecks = 1 bushel			36.37	0.02750
8 bushels = 1 quarter			290.9	0.003438
36 bushels = 1 chaldron			1309.	0.0007639

* A liter is 1,000 cu. cm., very nearly. Strictly, it is the volume of 1 kg. of water at 4° C. and 760 mm. Hg. The liter thus defined is larger than the cubic decimeter in the ratio 1.000027.

123. Cord and Board Measures (volume)

English	U. S.	Abbreviation	Metric eqivalent	
			Cubic meters	Reciprocal
	16 cubic ft. = 1 cord foot	cd. ft.	0.4530	2.208
	8 cord feet = 1 cord*	cd.	3.624	0.2759
	144 square in. = 1 board foot†	bd. ft.	.....	.....

* A cord is the volume of a rectangular parallelopiped, 8 ft. long, 4 ft. wide, and 4 ft. high = 128 cu. ft.

† The board foot is customarily 144 sq. in. with a thickness of 1 in. Less than 1 in. thick is customarily counted as 1 in.; for example, a board $\frac{1}{4}$ in. or $\frac{11}{16}$ in. thick would be counted 1 in. thick in board measure.

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124. Cubic Measure

English	U. S.	Abbreviation	Metric equivalent	
			Liters	Reciprocal
1 cubic inch	1 cubic inch	cu. in.	0.01639	61.02
1728 cubic inches = 1 cubic foot	1728 cubic inches = 1 cubic foot	cu. ft.	28.32	0.03532
27 cubic feet = 1 cubic yard	27 cubic feet = 1 cubic yard	cu. yd.	764.6	0.001308

125. Liquid Measure; Apothecaries

English	U. S.	Abbreviation	Metric equivalent	
			Liters	Reciprocal
1 minim			5.919×10^{-5}	1.689×10^{4}
	1 minim		6.161×10^{-5}	1.623×10^{4}
20 minims = 1 fluid scruple			0.001184	844.7
3 fluid scruples = 1 fluid drachm			0.003552	281.5
	60 minims = 1 fluid dram		0.003697	270.5
8 fluid drachms = 1 fluid ounce		fl. oz.	0.02841	35.20
	8 fluid drams = 1 fluid ounce	fl. oz.	0.02957	33.82

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126. Liquid Measure; General

English	U. S.	Abbreviation	Metric equivalent	
			Liters	Reciprocal
	1 gill		0.1183	8.453
1 gill			0.1421	7.039
	4 gills = 1 pint	pt.	0.4732	2.113
4 gills = 1 pint		pt.	0.5682	1.760
	2 pints = 1 quart	qt.	0.9464	1.057
2 pints = 1 quart		qt.	1.1365	0.8799
	4 quarts = 1 gallon	gal.	3.785	0.2642
4 quarts = 1 gallon		gal.	4.546	0.2200
	31½ gallons = 1 barrel *	bbl.	119.2	0.008389
31½ gallons = 1 half hogshead			143.2	0.006983
	42 gallons = 1 tierce		159.0	0.006289
42 gallons = 1 tierce			190.9	0.005238
	2 barrels = 1 hogshead	hhd.	238.4	0.004195
63 gallons = 1 hogshead		hhd.	286.4	0.003492
2 tierces = 1 puncheon			381.8	0.002619
2 hogsheads = 1 pipe			572.8	0.001746
2 pipes = 1 tun			1146.0	0.0008726

* The barrel and larger units are practically confined to the measurement of oil, wine or liquor volumes.

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127. Avoirdupois Weight (mass) for General Commodities

English	U. S.	Abbreviation	Metric equivalent	
			Grams	Reciprocal
1 grain	1 grain	gr.	0.064799	15.432
1 dram	1 dram		1.772	0.5643
16 drams = 1 ounce	16 drams = 1 ounce	oz.	28.35	0.03527
16 ounces = 1 pound	16 ounces = 1 pound	lb.	453.6	0.002205
or 7000 grains = 1 pound	or 7000 grains = 1 pound	lb.	453.6	0.002205
14 pounds = 1 stone	.....	.....	6,350	1.575×10^{-4}
	100 pounds = 1 hundredweight	cwt.	45,360	2.205×10^{-5}
8 stone = 112 lbs. = 1 hundredweight	.....	cwt.	50,800	1.969×10^{-5}
20 hundredweights = 1 long ton = 2240 lbs.	1 long ton	.....	1.0161×10^{6}	0.9842×10^{-6}
	20 hundredweight = 1 short ton	.....	0.9072×10^{6}	1.102×10^{-6}

128. Troy Weight (mass) for Gold, Silver, and some Precious Stones; also Jeweler's weight

English	U. S.	Abbreviation	Metric equivalent	
			Grams	Reciprocal
1 grain	1 grain	gr.	0.064799	15.432
24 grains = 1 pennyweight	24 grains = 1 pennyweight	dwt.	1.555	0.6431
20 pennyweights = 1 ounce	20 pennyweights = 1 ounce	os.	31.10	0.03215
12 ounces = 1 pound	12 ounces = 1 pound	lb.	373.2	0.002679
1 carat gold = 10 troy dwt.	1 carat gold = 10 troy dwt.	.....	15.55	0.06431
1 carat diamonds	1 carat diamonds	.....	0.2053	4.871
The international metric carat for diamonds is established at		.....	0.200	5.00

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CONVERSION TABLES

129. Density *

	Grams per cu. cm.	Reciprocal
1 lb. av. per sq. mil. ft.	2.936×10^{6}	0.3406×10^{-6}
1 lb. av. per circular mil-ft.	2.306×10^{6}	0.4337×10^{-6}
1 lb. av. per cu. in.	27.68	0.03613
1 lb. av. per cu. ft.	0.01602	62.43
1 grain per cu. in.	0.003954	252.9
1 lb. av. per cu. yd.	0.0005933	1,685

* Tables for converting **deg. Baumé** (liquid density) to specific gravity a 60 deg. fahr., and vice versa, are given in Circular No. 19, Bureau o Standards, pp. 31–35.

130. Time Intervals

	Mean solar			
	days	hours	mins.	secs.
1 mean solar year..	365.2	8,766	5.26×10^{5}	3.156×10^{7}
1 week of 7 days ..	7.0	168	1.008×10^{4}	6.048×10^{5}
1 mean solar day ..	1.0	24	1.440×10^{3}	8.640×10^{4}
1 siderial day.....	0.9973	23.93	1.436×10^{3}	8.616×10^{4}
1 mean solar hour	4.167×10^{-2}	1	60	3.60×10^{3}
1 siderial hour ...	4.155×10^{-2}	0.9973	59.83	3.590×10^{3}
1 mean solar minute.	6.944×10^{-4}	1.667×10^{-2}	1	60

131. Solid Angle

	Sphere	Hemisphere	Spherical right angle	Steradian
1 sphere.....	1	2	8	12.57
1 hemisphere.....	0.5	1	4	6.283
1 spherical right angle	0.125	0.25	1	1.573
1 steradian.....	0.07958	0.1592	0.6366	1

132. Force

	Grams Weight	Reciprocal	Dynes	Reciprocal
1 lb., weight avoird	453.6	0.002205	4.448×10^{5}	0.2248×10^{-5}
1 poundal.....	14.10	0.07092	1.383×10^{4}	0.7233×10^{-4}
1 grain, weight ...	0.06480	15.43	63.55	0.01573
1 gram, weight ...	1	1	980.665‡	0.0010197
1 short ton, weight	0.9072×10^{6}	1.102×10^{-6}	0.8896×10^{9}	1.124×10^{-9}
1 dyne.....	0.0010197	980.665‡	1	1
1 sthene.....	1.0197×10^{3}	0.9807×10^{-3}	10^{5}	10^{-5}

‡ The internationally accepted conventional value of gravitational a celeration at latitude 45 deg. and sea-level. This is usually adopte although later researches have indicated a slightly different value.

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123. Intensity of Pressure (Force per unit area)

	Bars or dynes per sq. cm.	Reciprocal	Grams per sq. cm.	Reciprocal	Standard atmospheres of 760 mm. mercury	Reciprocal
1 **Bar**, or dyne per sq. cm	1	1	1.0197×10^{-3}	980.665*	0.9871×10^{-6}	1.013×10^{6}
1 pièze or sthene per sq. m	10^{4}	10^{-4}	1.0197×10	0.9807×10^{-1}	0.9871×10^{-2}	1.013×10^{2}
1 **Megabar**	10^{6}	10^{-6}	1.0197×10^{3}	0.9807×10^{-3}	0.9871	1.013
1 gr. per sq. cm. or 1 cm. water	980.665*	1.0197×10^{-3}	1	1	0.9680×10^{-3}	1.033×10^{3}
1 standard atmosphere, 760 mm. mercury at 0° C.	1.0132×10^{6}	0.9871×10^{-6}	1.033×10^{3}	0.9680×10^{-3}	1	1
1 lb. avoird. per sq. ft	478.8	0.2089×10^{-2}	0.4883	2.048	0.4726×10^{-3}	2.116×10^{3}
1 kg. per sq. meter	98.07	1.020×10^{-3}	0.1	10	0.9680×10^{-4}	1.033×10^{4}
1 kg. per hectare	0.9807×10^{-3}	1.020×10^{3}	10^{-5}	10^{5}	0.9680×10^{-5}	1.033×10^{5}
1 mm. pure mercury	1.333×10^{3}	0.7501×10^{-3}	1.359	0.7358	1.316×10^{-3}	0.760×10^{3}
1 in. pure mercury at 0° C	3.386×10^{4}	0.2953×10^{-4}	34.53	0.02896	0.03343	29.91
1 lb. avoird. per sq. in	0.6894×10^{5}	1.450×10^{-5}	70.31	0.01422	0.06805	14.69
1 long ton per sq. ft	1.072×10^{6}	0.9328×10^{-6}	1,094	0.9141×10^{-3}	1.058	0.9451
1 short ton per sq. ft	0.9574×10^{6}	1.044×10^{-6}	976.5	1.024×10^{-3}	0.9451	1.058
1 ft. of water	2.989×10^{4}	0.3346×10^{-4}	30.48	0.03281	2.950×10^{-2}	33.90
1 in. of water	2.491×10^{3}	0.4014×10^{-3}	2.54	0.3937	2.459×10^{-3}	406.7

* See footnote to preceding table. The sea-level gravitational intensity at any latitude ϕ° is expressed by the formula:

$$g_{\phi} = 978.046\,(1+0.005302\sin^2\varphi - 0.7\times10^{-6}\sin^2 2\varphi) \text{ cm. per sec.}^2$$
$$= 980.632 - 2.5928\cos 2\varphi + 0.0068\cos^2 2\varphi \text{ cm. per sec.}^2$$

See Annuaire pour l'an 1914, p. 153. For elevations above sea-level, a subtraction of 0.192 cm. per sec.^{2} should be made per kilometer elevation. The range of variation in sea-level gravitation intensity according to the above formula is from 978.05 at the equator to 983.23 at the poles.

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134. Energy

	Ergs	Reciprocal	Gram-wt-cm. g = 980.7	Reciprocal	Gram-calories	Reciprocal
1 erg	1	1	1.0197×10^{-3}	980.7	0.2390×10^{-7}	4.184×10^{7}
1 joule	10^{7}	10^{-7}	1.0197×10^{4}	0.9807×10^{-4}	0.2390	4.184
1 gram-wt-cm. (g = 980.7)	980.7	1.0197×10^{-3}	1	1	0.2344×10^{-4}	4.266×10^{4}
1 gram-calorie	4.184×10^{7}	0.2390×10^{-7}	4.266×10^{4}	0.2344×10^{-4}	1	1
1 kilogram-calorie	4.184×10^{10}	0.2390×10^{-10}	4.266×10^{7}	0.2344×10^{-7}	1,000	10^{-3}
1 thermie or ton-calorie	4.184×10^{13}	0.2390×10^{-13}	4.266×10^{10}	0.2344×10^{-10}	1,000,000	10^{-6}
1 foot-grain (g = 980.7)	1.937×10^{3}	0.5163×10^{-3}	1.975	0.5063	0.4629×10^{-4}	2.160×10^{4}
1 foot-pound (g = 980.7)‡	1.356×10^{7}	0.7375×10^{-7}	1.383×10^{4}	0.7231×10^{-4}	0.3241	3.085
1 foot-long-ton (g = 980.7)	3.037×10^{10}	0.3293×10^{-10}	3.097×10^{7}	0.3229×10^{-7}	0.7258×10^{3}	1.378×10^{-3}
1 foot-short-ton (g = 980.7)	2.712×10^{10}	0.3687×10^{-10}	2.766×10^{7}	0.3615×10^{-7}	0.6482×10^{3}	1.543×10^{-3}
1 British thermal unit	1.054×10^{10}	0.9488×10^{-10}	1.075×10^{7}	0.9302×10^{-7}	0.251×10^{3}	3.970×10^{-3}
1 watt-hour	3.600×10^{10}	0.2778×10^{-10}	3.671×10^{7}	0.2724×10^{-7}	0.8604×10^{3}	1.162×10^{-3}
1 kilowatt-hour	3.600×10^{13}	0.2778×10^{-13}	3.671×10^{10}	0.2724×10^{-10}	0.8604×10^{6}	1.162×10^{-6}
1 horse-power-hour* (746 watt-hrs.)	2.686×10^{13}	0.3723×10^{-13}	2.739×10^{10}	0.3651×10^{-10}	0.6420×10^{6}	1.558×10^{-6}
1 horse-power-hour (745.7 watt-hrs., g = 980.7).	2.684×10^{13}	0.3726×10^{-13}	2.737×10^{10}	0.3654×10^{-10}	0.6415×10^{6}	1.559×10^{-6}
1 metric horse-power-hour (736 watt-hrs.).**	2.650×10^{13}	0.3774×10^{-13}	2.702×10^{10}	0.3701×10^{-10}	0.6334×10^{6}	1.579×10^{-6}
1 metric horse-power-hour (735.5 watt-hrs., g = 980.7).	2.648×10^{13}	0.3776×10^{-13}	2.700×10^{10}	0.3704×10^{-10}	0.6328×10^{6}	1.580×10^{-6}
1 kilojoule	10^{10}	10^{-10}	1.0197×10^{7}	0.9807×10^{-7}	239.0	4.184×10^{-3}

* For g = 981.2 for approximate latitude of London.

** For g = 981.3 for approximate latitude of Berlin.

‡ The local foot-pound varies between the equator and the poles, according to the local intensity of gravitation between the limits 1.352 and 1.359 joules.

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136. Power

	Watts	Reciprocal	Kilowatts	Reciprocal	Ergs per sec.	Reciprocal
1 British horse-power (g−981.2*).....	746.0	1.340×10^{-3}	0.7460	1.340	7.46×10^{9}	1.340×10^{-10}
1 British horse-power (g−980.7).....	745.7	1.341×10^{-3}	0.7457	1.341	7.457×10^{9}	1.341×10^{-10}
1 metric horse-power (g%981.3).....	736.0	1.359×10^{-3}	0.7360	1.359	7.36×10^{9}	1.359×10^{-10}
1 metric horse-power (g%980.7).....	735.5	1.360×10^{-3}	0.7355	1.360	7.355×10^{9}	1.360×10^{-10}
1 Poncelet, 100 kgrm. per second.....	980.7	1.020×10^{-3}	0.9807	1.020	9.807×10^{9}	1.020×10^{-10}
1 British thermal unit per hour.....	0.2928	3.415	0.2928×10^{-3}	3.415×10^{3}	2.928×10^{6}	3.415×10^{-7}
1 gram-calorie per second.....	4.184	0.2390	4.184×10^{-3}	0.2390×10^{3}	4.184×10^{7}	0.2390×10^{-7}
1 gram-calorie per minute.....	6.972×10^{-2}	0.1434×10^{2}	6.972×10^{-5}	0.1434×10^{5}	6.972×10^{5}	0.1434×10^{-5}
1 gram-calorie per hour.....	1.162×10^{-3}	0.8606×10^{3}	1.162×10^{-6}	0.8606×10^{6}	1.162×10^{4}	0.8606×10^{-4}
1 kilogram-calorie per second.....	4.184×10^{3}	0.2390×10^{-3}	4.184	0.2390	4.184×10^{10}	0.2390×10^{-10}
1 kilogram-calorie per minute.....	6.972×10^{1}	0.1434×10^{-1}	6.972×10^{-2}	0.1434×10^{2}	6.972×10^{8}	0.1434×10^{-8}
1 kilogram-calorie per hour.....	1.162	0.8606	1.162×10^{-3}	0.8606×10^{3}	1.162×10^{7}	0.8606×10^{-7}
1 thermie per second.....	4.184×10^{6}	0.2390×10^{-3}	4.184×10^{3}	0.2390×10^{-3}	4.184×10^{13}	0.2390×10^{-13}
1 thermie per minute.....	6.972×10^{4}	0.1434×10^{-4}	6.972×10^{1}	0.1434×10^{-1}	6.972×10^{11}	0.1434×10^{-11}
1 thermie per hour.....	1.162×10^{3}	0.8606×10^{-3}	1.162	0.8606	1.162×10^{10}	0.8606×10^{-10}
1 water horse-power, 3,960 U. S. gallons per min. lifted 1 ft.	746.7	1.339×10^{-3}	0.7467	1.339	0.7467×10^{10}	1.339×10^{-10}
1 boiler horse-power†.....	9804	1.020×10^{-4}	9.804	1.020×10^{-1}	9.804×10^{10}	1.020×10^{-11}
1 foot-pound per sec. against standard g.	1.356	0.7375	1.356×10^{-3}	737.5	1.356×10^{7}	0.7375×10^{-7}
1 foot-pound per min. against standard g.	0.02260	44.25	0.2260×10^{-4}	4.425×10^{-4}	0.2260×10^{-6}	4.425×10^{-6}
1 kilogm-meter per sec. against standard g.	9.807	1.020×10^{-1}	9.807×10^{-3}	1.020×10^{2}	0.9807×10^{8}	1.020×10^{-8}

* The question is often raised as to whether a British horse-power should be considered to be 33,000 foot-pounds per min. under the gravitational force of London (g=981.2), corresponding to 746.0 watts, or under the standard gravitational force conventional for latitude 45° (g=980.665) corresponding to 745.7 watts, and similarly for the metric horse-power. Both values are therefore offered.

† 34.5 avoird. lb. water evaporated per hour from and at 212 deg. fahr. to steam at this temperature.

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136. Torque

	Grams perp. cm.	Reciprocal	Dynes perp. cm.	Reciprocal
1 lb.-perp.-ft.*	1.383×10^{4}	0.7233×10^{-4}	1.356×10^{7}	0.7375×10^{-7}
1 g.-perp.-cm	1	1	980.665	0.0010197
1 dyne-perp.-cm	0.0010197	980.665	1	1

137. Linear Velocity

	Metric equivalent	
	Meters per sec.	Reciprocal
1 ft.-per-sec	0.3048	3.281
1 ft.-per-min	0.005080	196.9
1 mile-per-hr	0.4470	2.237
1 km.-per-hr	0.2778	3.60
1 knot, or naut-per-hr	0.5148	1.943

138. Linear Acceleration

	Meters per sec. per sec.	Reciprocal	Km. per hr. per sec.	Reciprocal
1 ft. per sec. per sec.	0.3048	3.281	1.097	0.9114
1 mile per hr. per sec.	0.4470	2.237	1.609	0.6214
Standard gravitation g	9.80665	0.10197	35.30	0.02833
1 m. per sec. per sec.	1	1	3.600	0.2778
1 km. per hr. per sec.	0.2778	3.600	1	1

139. Conversion of Angles (plane)

Angles	Degrees	Reciprocal	Grades	Reciprocal	Radian	Reciprocal
1 degree	1	1	1.1111	0.900	0.01745	57.3
1 grade	0.9	1.111	1	1	0.01571	63.6
1 radian	57.30	0.01745	63.66	0.01571	1	1
1 quadrant	90°	0.01111	100	0.010	$\pi/2=1.571$	0.636
1 revolution	360°	0.002778	400	0.00250	$2\pi=6.283$	0.159
π radians	180°	0.005556	200	0.005	$\pi=3.142$	0.318
$\pi/2$ radians	90°	0.01111	100	0.010	$\pi/2=1.571$	0.636
$\pi/4$ radians	45°	0.02222	50	0.020	$\pi/4=0.7854$	1.273
2π radians	360°	0.002778	400	0.0025	$2\pi=6.283$	0.159

140. Linear Mass

	Gram per meter	Reciprocal
1 lb. per linear yard	496.1	0.002016
1 lb. per linear foot	1488	0.0006720

* A torque is the product of a force and a length taken perpendicular thereto. Its dimensions are therefore those of force $\times -jL$ where $j=\sqrt{-}$ or $-jL^2M^1T^{-2}$. Any element of angle is also the ratio of an element of a length to the length of a radius perpendicular thereto, or has dimensio $jL/L=j$. The product of torque and the angle through which it advanc is thus $-jL^2M^1T^{-2}\times j=L^2M^1T^{-2}$ which are the dimensions of work. the foregoing direction symbols are neglected, a torque appears to have t same dimensions and nature as a work, which is illogical. A torque of 1 force acting at a radius of 1 cm. is thus correctly to be expressed as a gra perpendicular centimeter rather than as a gram centimeter.

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141. Angular Velocity

	Degrees per sec.	Reciprocal	Grades per sec.	Reciprocal	Radians per sec.	Reciprocal	Revs. per sec.	Reciprocal
1 degree per second	1	1	1.111	0.90	0.01745	57.30	0.002778	360
1 grade per second	0.90	1.111	1	1	0.01571	63.67	0.0025	400
1 radian per sec	57.30	0.01745	63.67	0.01571	1	1	0.1592	6.283
1 rev. per sec	360	0.002778	400	0.0025	6.283	0.1592	1	1
1 degree per minute	0.01667	60	0.01852	54	0.0002909	3,438	0.4630×10^{-4}	21,600
1 grade per minute	0.0150	66.667	0.01667	60	0.0002618	3,820	0.4167×10^{-4}	24,000
1 radian per minute	0.9549	1.047	1.061	0.9425	0.01667	60	0.002653	376.9
1 rev. per minute	6.0	0.1667	6.667	0.15	0.1047	9.551	0.01667	60
1 degree per hour	0.2778×10^{-3}	3,600	0.3086×10^{-3}	3,240	0.4848×10^{-5}	206,300	0.7716×10^{-6}	1.296×10^{6}
1 grade per hour	0.25×10^{-3}	4 000	0.2778×10^{-3}	3,600	0.4363×10^{-5}	229,200	0.6944×10^{-6}	1.44×10^{6}
1 radian per hour	0.01592	62.83	0.01769	56.55	0.2778×10^{-3}	3,600	0.4421×10^{-5}	2.262×10^{4}
1 rev. per hour	0.1	10	0.1111	9.00	0.1745×10^{-3}	573.10	0.2778×10^{-3}	3.6×10^{3}

142. Flow of Water

	Liters per sec.	Reciprocal	Liters per min.	Reciprocal	Liters per hr.	Reciprocal
1 cu. ft. per sec	28.32	0.03531	1,699	0.5886×10^{-3}	1.020×10^{6}	0.9804×10^{-6}
1 cu. ft. per min	0.4719	2.119	28.32	0.03531	1.699×10^{3}	0.5886×10^{-3}
1 cu. yd. per sec	764.5	1.308×10^{-3}	4.587×10^{4}	0.2180×10^{-4}	2.752×10^{6}	0.3634×10^{-6}
1 cu. yd. per min	12.74	0.07849	764.5	1.308×10^{-3}	4.587×10^{4}	0.2180×10^{-4}
1 liter per sec	1	1	60	0.01667	3,600	0.2778×10^{-6}
1 liter per min	0.01667	60	1	1	60	0.01667
1 U. S. gal. per sec	3.785	0.2642	227.1	0.4403×10^{-2}	1.363×10^{4}	0.7337×10^{-4}
1 U. S. gal. per min	0.06308	15.85	3.785	0 2642	227.1	0.4403×10^{-2}
1 lb. avoird. per sec	0 4536	2.205	27.22	0.03674	1.633×10^{3}	0.6124×10^{-3}
1 lb avoird. per min	0.007560	132 3	0.4536	2.205	27.22	0.03674
1 British gal. per sec	4.546	0 2200	272.8	0.3666×10^{-2}	1.637×10^{4}	0.6109×10^{-4}
1 British gal. per min	0 07577	13 20	4.546	0.2200	272.8	0.3666×10^{-2}
1 miner's in. of 1.5 cu. ft. per min *	0.7079	1.413	42.47	0.02355	2.549×10^{3}	0.3923×10^{-3}

* The miner's inch is ordinarily defined as the flow of water through an aperture 1 in. square under a head of 0.55 ft.; but the unit is not very definite and varies in different States. An average value is 1.5 cu. ft. per min.

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143. Storage of Water

1 acre-ft. = 325,800 U. S. gal. = 43,560 cu. ft. = 1613 cu. yd. = 1234 cu. m
1 gal. = 0.3069×10^{-5} acre-ft.
1 cu. ft. = 0.2298×10^{-4} acre-ft.
1 cu. yd. = 0.00062 acre-ft.
1 cu. m. = 0.000811 acre-ft.

144. Temperature

Scale	Freezing point of water	Boiling point of water	Interval
Fahrenheit.....	32 deg.	212 deg.	180 deg.
Centigrade.....	0 deg.	100 deg.	100 deg.
Réaumur.....	0 deg.	80 deg.	80 deg.

1 deg. fahr. = 0.5556 or (5/9) deg. cent. = 0.4444 or (4/9) deg. réa.
1 deg. cent. = 0.8000 deg. réa. = 1.800 deg. fahr.
1 deg. réa. = 2.250 deg. fahr. = 1.250 deg. cent.
Absolute zero = −273.1 deg. cent. = −491.6 deg. fahr. = −218. deg. réaumur.

T_{abs} = 273.1 + deg. cent. (in cent. scale)
T_{abs} = 491.6 + deg. fahr. (in fahr. scale)
T_{abs} = 218.5 + deg. réaumur (in réaumur scale)

145. Mechanical equivalent of heat.

1 B.t.u. = 1,054 joules = 777.5 ft-lb. = 0.2928 watt-hr. = 0.0003927 h.p-hr.
1 joule = 0.7375 ft.-lb. = 0.0009488 B.t.u. = 0.0002778 watt-hr.
1 ft.-lb. = 1.356 joules = 0.001286 B.t.u. = 0.0003766 watt-hr.
1 watt-hr. = 3,600 joules = 2.655 ft.-lb. = 3.415 B.t.u.
Also see Par. **134** on energy conversion factors.

146. Electrical resistivity. Resistivity (see also Par. **58** and **115**) m be defined quantitatively either in terms of "mass resistivity" ρ_m, or "volume resistivity" ρ_v. The defining equation of mass resistivity is

$$\rho_m = \frac{R}{L} \cdot \frac{M}{L} \qquad \frac{\text{gram ohms}}{\text{meter}^2} \qquad (1$$

It is the product of the linear resistance in ohms per meter and the line mass in grams per meter. R is the resistance of the wire in ohms, M i mass in grams, and L its length in meters. A uniform copper wire of 1 per cent. conductivity 1 meter long, at 20 deg. cent., and weighing 1 g would have a resistance of 0.15328 international ohm. The defining equ tion of volume resistivity is

$$\rho_v = R\frac{A}{L} = \frac{1}{\delta}\left(\frac{R}{L} \cdot \frac{M}{L}\right) = \frac{\rho_m}{\delta} \qquad \text{microhm-cm.} \qquad (1$$

where R is the resistance of the wire in microhms, A is its uniform cro sectional area in sq cm., L its length in cm. and δ the density of the wi At 20 deg. cent., a wire of 100 per cent. conductivity 1 cm. long and of sq. cm. in cross-section would have a resistance of 1.7241 microhms.

Since, in accurate measurements of wire conductivity, the length, weig and resistance of the wire are always determined, the mass resistivity more fundamental than the volume resistivity in engineering. Their rat is the density δ when the units employed are identical in both. The densi of copper is taken as 8.90 gm. per cu. cm. at 0 deg. cent. and 8.89 at deg cent., the temperature coefficient of linear expansion being 17×10 Owing to the effects of expansion the temperature coefficients of the tv resistivities are not identical. See Sec. 4 for further discussion and numeric values of resistivity, density and temperature coefficients. Factors f converting resistivity expressed in terms of any of the customary units corresponding values in the other units are given in the following paragrap

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147. Resistivity Conversion Factors

Unit of resistivity	Factors for changing values of resistivity expressed in units in left-hand column to values expressed in units below					
	Meter, gram	Mile, pound	Microhm-cm.	Microhm-inch	Mil, foot	Meter, mm.
Meter, gram		5708	$10^2 d^{-1}$	$39.37 d^{-1}$	$601.5 d^{-1}$	d^{-1}
Mile, pound	1.752×10^{-4}		$0.01752 d^{-1}$	$6.898 \times 10^{-3} d^{-1}$	$0.1054 d^{-1}$	$1.752 \times 10^{-4} d^{-1}$
Microhm-cm	$10^{-2} d$	$57.08 d$		0.3937	6.015	10^{-2}
Microhm-in	$0.02540 d$	$145.0 d$	2.540		15.28	0.02540
Mil, foot	$1.662 \times 10^{-3} d$	$9.492 d$	0.1662	0.0545		1.662×10^{-3}
Meter, mm.^{2}	d	$5708 d$	10^2	39.37	601.5	

The factor d in the foregoing table is the density of the conductor, at the same temperature as the value of resistivity; 20 deg. cent. is standard for copper. For values of resistivity of various conductor materials, see Sec. 4.

148. Current densities.

English	Metric equivalent	
	Amp. per sq. cm.	Reciprocal
1 ampere per square yard	1.196×10^{-4}	8.361×10^3
1 ampere per square foot	1.076×10^{-3}	9.29×10^2
1 ampere per square inch	0.1550	6.452
1 ampere per square mil	1.550×10^6	6.452×10^{-6}
1 ampere per circular mil	1.973×10^5	5.068×10^{-6}

149. Useful Constants. Base of the hyperbolic system of logarithms $= e = 2.7183$ to the nearest unit in five significant figures; it is not a commensurate quantity.

Ratio of circumference to diameter of circle $= \pi = 3.1416$ (incommensurate).

	Numeric	Reciprocal
e	2.7183	0.36788
$\log_{10} e$	0.434295	2.302585
π	3.1416	0.31831
$\pi/4$	0.7854	1.2732
π^2	9.8696	0.10132
$\sqrt{\pi}$	1.7725	0.56419
$\sqrt{2}$	1.4142	0.70711
$\sqrt{3}$	1.7321	0.57733

1 radian = 57.296 deg. = 57 deg., 17 min. and 45 sec.

An arc of 1 deg., in terms of its radius = 0.017453.

For further conversion factors of circular measure, see Par. **134** on angles.

Both e and π are incommensurate.

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150. Conversion of Logarithms. For converting logarithms to the base a, to another base b:

$$\log_b x = \frac{\log_a x}{\log_a b} \tag{12}$$

$$\log_a b \times \log_b a = 1 \tag{13}$$

Common or **Briggs logarithms** are computed from the base of 10 while **hyperbolic logarithms** are computed from the base e or 2.7183 Therefore

$$\log_e x = \frac{\log_{10} x}{\log_{10} e} \tag{14}$$

151. The Greek Alphabet

Name	Large	Small	Commonly used to designate
alpha	A	α	angles, coefficients.
beta	B	β	angles, coefficients.
gamma	Γ	γ	specific gravity.
delta	Δ	δ	density, variation.
epsilon	E	ϵ	base of hyperbolic logarithms.
zeta	Z	ζ	co-ordinates, coefficients.
eta	H	η	hysteresis (Steinmetz) coefficient, efficiency
theta	Θ	θ	angular phase displacement, time constant.
iota	I	ι	
kappa	K	κ	dielectric constant, susceptibility.
lambda	Λ	λ	conductivity.
mu	M	μ	permeability.
nu	N	ν	reluctivity.
xi	Ξ	ξ	output coefficient.
omicron	O	o	
pi	Π	π	circumference ÷ diameter.
rho	P	ρ	resistivity.
sigma	Σ	σ	(cap.), summation; leakage coefficient.
tau	T	τ	time-phase displacement, time constant
upsilon	Υ	υ	
phi	Φ	ϕ	flux.
chi	X	χ	
psi	Ψ	ψ	angular velocity in time.
omega	Ω	ω	(small), angular velocity in space.

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MATHEMATICAL TABLES

153. Natural Sines and Cosines

NOTE.—For cosines use right-hand column of degrees and lower line of tenths.

Deg.	°0.0	°0.1	°0.2	°0.3	°0.4	°0.5	°0.6	°0.7	°0.8	°0.9	
0°	0.0000	0.0017	0.0035	0.0052	0.0070	0.0087	0.0105	0.0122	0.0140	0.0157	89
1	0.0175	0.0192	0.0209	0.0227	0.0244	0.0262	0.0279	0.0297	0.0314	0.0332	88
2	0.0349	0.0366	0.0384	0.0401	0.0419	0.0436	0.0454	0.0471	0.0488	0.0506	87
3	0.0523	0.0541	0.0558	0.0576	0.0593	0.0610	0.0628	0.0645	0.0663	0.0680	86
4	0.0698	0.0715	0.0732	0.0750	0.0767	0.0785	0.0802	0.0819	0.0837	0.0854	85
5	0.0872	0.0889	0.0906	0.0924	0.0941	0.0958	0.0976	0.0993	0.1011	0.1028	84
6	0.1045	0.1063	0.1080	0.1097	0.1115	0.1132	0.1149	0.1167	0.1184	0.1201	83
7	0.1219	0.1236	0.1253	0.1271	0.1288	0.1305	0.1323	0.1340	0.1357	0.1374	82
8	0.1392	0.1409	0.1426	0.1444	0.1461	0.1478	0.1495	0.1513	0.1530	0.1547	81
9	0.1564	0.1582	0.1599	0.1616	0.1633	0.1650	0.1668	0.1685	0.1702	0.1719	80°
10°	0.1736	0.1754	0.1771	0.1788	0.1805	0.1822	0.1840	0.1857	0.1874	0.1891	79
11	0.1908	0.1925	0.1942	0.1959	0.1977	0.1994	0.2011	0.2028	0.2045	0.2062	78
12	0.2079	0.2096	0.2113	0.2130	0.2147	0.2164	0.2181	0.2198	0.2215	0.2232	77
13	0.2250	0.2267	0.2284	0.2300	0.2317	0.2334	0.2351	0.2368	0.2385	0.2402	76
14	0.2419	0.2436	0.2453	0.2470	0.2487	0.2504	0.2521	0.2538	0.2554	0.2571	75
15	0.2588	0.2605	0.2622	0.2639	0.2656	0.2672	0.2689	0.2706	0.2723	0.2740	74
16	0.2756	0.2773	0.2790	0.2807	0.2823	0.2840	0.2857	0.2874	0.2890	0.2907	73
17	0.2924	0.2940	0.2957	0.2974	0.2990	0.3007	0.3024	0.3040	0.3057	0.3074	72
18	0.3090	0.3107	0.3123	0.3140	0.3156	0.3173	0.3190	0.3206	0.3223	0.3239	71
19	0.3256	0.3272	0.3289	0.3305	0.3322	0.3338	0.3355	0.3371	0.3387	0.3404	70°
20°	0.3420	0.3437	0.3453	0.3469	0.3486	0.3502	0.3518	0.3535	0.3551	0.3567	69
21	0.3584	0.3600	0.3616	0.3633	0.3649	0.3665	0.3681	0.3697	0.3714	0.3730	68
22	0.3746	0.3762	0.3778	0.3795	0.3811	0.3827	0.3843	0.3859	0.3875	0.3891	67
23	0.3907	0.3923	0.3939	0.3955	0.3971	0.3987	0.4003	0.4019	0.4035	0.4051	66
24	0.4067	0.4083	0.4099	0.4115	0.4131	0.4147	0.4163	0.4179	0.4195	0.4210	65
25	0.4226	0.4242	0.4258	0.4274	0.4289	0.4305	0.4321	0.4337	0.4352	0.4368	64
26	0.4384	0.4399	0.4415	0.4431	0.4446	0.4462	0.4478	0.4493	0.4509	0.4524	63
27	0.4540	0.4555	0.4571	0.4586	0.4602	0.4617	0.4633	0.4648	0.4664	0.4679	62
28	0.4695	0.4710	0.4726	0.4741	0.4756	0.4772	0.4787	0.4802	0.4818	0.4833	61
29	0.4848	0.4863	0.4879	0.4894	0.4909	0.4924	0.4939	0.4955	0.4970	0.4985	60°
30°	0.5000	0.5015	0.5030	0.5045	0.5060	0.5075	0.5090	0.5105	0.5120	0.5135	59
31	0.5150	0.5165	0.5180	0.5195	0.5210	0.5225	0.5240	0.5255	0.5270	0.5284	58
32	0.5299	0.5314	0.5329	0.5344	0.5358	0.5373	0.5388	0.5402	0.5417	0.5432	57
33	0.5446	0.5461	0.5476	0.5490	0.5505	0.5519	0.5534	0.5548	0.5563	0.5577	56
34	0.5592	0.5606	0.5621	0.5635	0.5650	0.5664	0.5678	0.5693	0.5707	0.5721	55
35	0.5736	0.5750	0.5764	0.5779	0.5793	0.5807	0.5821	0.5835	0.5850	0.5864	54
36	0.5878	0.5892	0.5906	0.5920	0.5934	0.5948	0.5962	0.5976	0.5990	0.6004	53
37	0.6018	0.6032	0.6046	0.6060	0.6074	0.6088	0.6101	0.6115	0.6129	0.6143	52
38	0.6157	0.6170	0.6184	0.6198	0.6211	0.6225	0.6239	0.6252	0.6266	0.6280	51
39	0.6293	0.6307	0.6320	0.6334	0.6347	0.6361	0.6374	0.6388	0.6401	0.6414	50°
40°	0.6428	0.6441	0.6455	0.6468	0.6481	0.6494	0.6508	0.6521	0.6534	0.6547	49
41	0.6561	0.6574	0.6587	0.6600	0.6613	0.6626	0.6639	0.6652	0.6665	0.6678	48
42	0.6691	0.6704	0.6717	0.6730	0.6743	0.6756	0.6769	0.6782	0.6794	0.6807	47
43	0.6820	0.6833	0.6845	0.6858	0.6871	0.6884	0.6896	0.6909	0.6921	0.6934	46
44	0.6947	0.6959	0.6972	0.6984	0.6997	0.7009	0.7022	0.7034	0.7046	0.7059	45
	°1.0	°0.9	°0.8	°0.7	°0.6	°0.5	°0.4	°0.3	°0.2	°0.1	Deg.

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Natural Sines and Cosines.—*Concluded*

Deg.	°0.0	°0.1	°0.2	°0.3	°0.4	°0.5	°0.6	°0.7	°0.8	°0.9	
45	0.7071	0.7083	0.7096	0.7108	0.7120	0.7133	0.7145	0.7157	0.7169	0.7181	44
46	0.7193	0.7206	0.7218	0.7230	0.7242	0.7254	0.7266	0.7278	0.7290	0.7302	43
47	0.7314	0.7325	0.7337	0.7349	0.7361	0.7373	0.7385	0.7396	0.7408	0.7420	42
48	0.7431	0.7443	0.7455	0.7466	0.7478	0.7490	0.7501	0.7513	0.7524	0.7536	41
49	0.7547	0.7559	0.7570	0.7581	0.7593	0.7604	0.7615	0.7627	0.7638	0.7649	40°
50°	0.7660	0.7672	0.7683	0.7694	0.7705	0.7716	9.7727	0.7738	0.7749	0.7760	39
51	0.7771	0.7782	0.7793	0.7804	0.7815	0.7826	0.7837	0.7848	0.7859	0.7869	38
52	0.7880	0.7891	0.7902	0.7912	0.7923	0.7934	0.7944	0.7955	0.7965	0.7976	37
53	0.7986	0.7997	0.8007	0.8018	0.8028	0.8039	0.8049	0.8059	0.8070	0.8080	36
54	0.8090	0.8100	0.8111	0.8121	0.8131	0.8141	0.8151	0.8161	0.8171	0.8181	35
55	0.8192	0.8202	0.8211	0.8221	0.8231	0.8241	0.8251	0.8261	0.8271	0.8281	34
56	0.8290	0.8300	0.8310	0.8320	0.8329	0.8339	0.8348	0.8358	0.8368	0.8377	33
57	0.8387	0.8396	0.8406	0.8415	0.8425	0.8434	0.8443	0.8453	0.8462	0.8471	32
58	0.8480	0.8490	0.8499	0.8508	0.8517	0.8526	0.8536	0.8545	0.8554	0.8563	31
59	0.8572	0.8581	0.8590	0.8599	0.8607	0.8616	0.8625	0.8634	0.8643	0.8652	30°
60°	0.8660	0.8669	0.8678	0.8686	0.8695	0.8704	0.8712	0.8721	0.8729	0.8738	29
61	0.8746	0.8755	0.8763	0.8771	0.8780	0.8788	0.8796	0.8805	0.8813	0.8821	28
62	0.8829	0.8838	0.8846	0.8854	0.8862	0.8870	0.8878	0.8886	0.8894	0.8902	27
63	0.8910	0.8918	0.8926	0.8934	0.8942	0.8949	0.8957	0.8965	0.8973	0.8980	26
64	0.8988	0.8996	0.9003	0.9011	0.9018	0.9026	0.9033	0.9041	0.9048	0.9056	25
65	0.9063	0.9070	0.9078	0.9085	0.9092	0.9100	0.9107	0.9114	0.9121	0.9128	24
66	0.9135	0.9143	0.9150	0.9157	0.9164	0.9171	0.9178	0.9184	0.9191	0.9198	23
67	0.9205	0.9212	0.9219	0.9225	0.9232	0.9239	0.9245	0.9252	0.9259	0.9265	22
68	0.9272	0.9278	0.9285	0.9291	0.9298	0.9304	0.9311	0.9317	0.9323	0.9330	21
69	0.9336	0.9342	0.9348	0.9354	0.9361	0.9367	0.9373	0.9379	0.9385	0.9391	20°
70°	0.9397	0.9403	0.9409	0.9415	0.9421	0.9426	0.9432	0.9438	0.9444	0.9449	19
71	0.9455	0.9461	0.9466	0.9472	0.9478	0.9483	0.9489	0.9494	0.9500	9.9505	18
72	0.9511	0.9516	0.9521	0.9527	0.9532	0.9537	0.9542	0.9548	0.9553	0.9558	17
73	0.9563	0.9568	0.9573	0.9578	0.9583	0.9588	0.9593	0.9598	0.9603	0.9608	16
74	0.9613	0.9617	0.9622	0.9627	0.9632	0.9636	0.9641	0.9646	0.9650	0.9655	15
75	0.9659	0.9664	0.9668	0.9673	0.9677	0.9681	0.9686	0.9690	0.9694	0.9699	14
76	0.9703	0.9707	0.9711	0.9715	0.9720	0.9724	0.9728	0.9732	0.9736	0.9740	13
77	0.9744	0.9748	0.9751	0.9755	0.9759	0.9763	0.9767	0.9770	0.9774	0.9778	12
78	0.9781	0.9785	0.9789	0.9792	0.9796	0.9799	0.9803	0.9806	0.9810	0.9813	11
79	0.9816	0.9820	0.9823	0.9826	0.9829	0.9833	0.9836	0.9839	0.9842	0.9845	10°
80°	0.9848	0.9851	0.9854	0.9857	0.9860	0.9863	0.9866	0.9869	0.9871	0.9874	9
81	0.9877	0.9880	0.9882	0.9885	0.9888	0.9890	0.9893	0.9895	0.9898	0.9900	8
82	0.9903	0.9905	0.9907	0.9910	0.9912	0.9914	0.9917	0.9919	0.9921	0.9923	7
83	0.9925	0.9928	0.9930	0.9932	0.9934	0.9936	0.9938	0.9940	0.9942	0.9943	6
84	0.9945	0.9947	0.9949	0.9951	0.9952	0.9954	0.9956	0.9957	0.9959	0.9960	5
85	0.9962	0.9963	0.9965	0.9966	0.9968	0.9969	0.9971	0.9972	0.9973	0.9974	4
86	0.9976	0.9977	0.9978	0.9979	0.9980	0.9981	0.9982	0.9983	0.9984	0.9985	3
87	0.9986	0.9987	0.9988	0.9989	0.9990	0.9990	0.9991	0.9992	0.9993	0.9993	2
88	0.9994	0.9995	0.9995	0.9996	0.9996	0.9997	0.9997	0.9997	0.9998	0.9998	1
89	0.9998	0.9999	0.9999	0.9999	0.9999	1.000	1.000	1.000	1.000	1.000	0°
	°1.0	°0.9	°0.8	°0.7	°0.6	°0.5	°0.4	°0.3	°0.2	°0.1	Deg

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154. Natural Tangents and Cotangents

NOTE.—For cotangents use right-hand column of degrees and lower line of tenths

Deg	°0.0	°0.1	°0.2	°0.3	°0.4	°0.5	°0.6	°0.7	°0.8	°0.9	
0°	0.0000	0.0017	0.0035	0.0052	0.0070	0.0087	0.0105	0.0122	0.0140	0.0157	89
1	0.0175	0.0192	0.0209	0.0227	0.0244	0.0262	0.0279	0.0297	0.0314	0.0332	88
2	0.0349	0.0367	0.0384	0.0402	0.0419	0.0437	0.0454	0.0472	0.0489	0.0507	87
3	0.0524	0.0542	0.0559	0.0577	0.0594	0.0612	0.0629	0.0647	0.0664	0.0682	86
4	0.0699	0.0717	0.0734	0.0752	0.0769	0.0787	0.0805	0.0822	0.0840	0.0857	85
5	0.0875	0.0892	0.0910	0.0928	0.0945	0.0963	0.0981	0.0998	0.1016	0.1033	84
6	0.1051	0.1069	0.1086	0.1104	0.1122	0.1139	0.1157	0.1175	0.1192	0.1210	83
7	0.1228	0.1246	0.1263	0.1281	0.1299	0.1317	0.1334	0.1352	0.1370	0.1388	82
8	0.1405	0.1423	0.1441	0.1459	0.1477	0.1495	0.1512	0.1530	0.1548	0.1566	81
9	0.1584	0.1602	0.1620	0.1638	0.1655	0.1673	0.1691	0.1709	0.1727	0.1745	80°
10°	0.1763	0.1781	0.1799	0.1817	0.1835	0.1853	0.1871	0.1890	0.1908	0.1926	79
11	0.1944	0.1962	0.1980	0.1998	0.2016	0.2035	0.2053	0.2071	0.2089	0.2107	78
12	0.2126	0.2144	0.2162	0.2180	0.2199	0.2217	0.2235	0.2254	0.2272	0.2290	77
13	0.2309	0.2327	0.2345	0.2364	0.2382	0.2401	0.2419	0.2438	0.2456	0.2475	76
14	0.2493	0.2512	0.2530	0.2549	0.2568	0.2586	0.2605	0.2623	0.2642	0.2661	75
15	0.2679	0.2698	0.2717	0.2736	0.2754	0.2773	0.2792	0.2811	0.2830	0.2849	74
16	0.2867	0.2886	0.2905	0.2924	0.2943	0.2962	0.2981	0.3000	0.3019	0.3038	73
17	0.3057	0.3076	0.3096	0.3115	0.3134	0.3153	0.3172	0.3191	0.3211	0.3230	72
18	0.3249	0.3269	0.3288	0.3307	0.3327	0.3346	0.3365	0.3385	0.3404	0.3424	71
19	0.3443	0.3463	0.3482	0.3502	0.3522	0.3541	0.3561	0.3581	0.3600	0.3620	70°
20°	0.3640	0.3659	0.3679	0.3699	0.3719	0.3739	0.3759	0.3779	0.3799	0.3819	69
21	0.3839	0.3859	0.3879	0.3899	0.3919	0.3939	0.3959	0.3979	0.4000	0.4020	68
22	0.4040	0.4061	0.4081	0.4101	0.4122	0.4142	0.4163	0.4183	0.4204	0.4224	67
23	0.4245	0.4265	0.4286	0.4307	0.4327	0.4348	0.4369	0.4390	0.4411	0.4431	66
24	0.4452	0.4473	0.4494	0.4515	0.4536	0.4557	0.4578	0.4599	0.4621	0.4642	65
25	0.4663	0.4684	0.4706	0.4727	0.4748	0.4770	0.4791	0.4813	0.4834	0.4856	64
26	0.4877	0.4899	0.4921	0.4942	0.4964	0.4986	0.5008	0.5029	0.5051	0.5073	63
27	0.5095	0.5117	0.5139	0.5161	0.5184	0.5206	0.5228	0.5250	0.5272	0.5295	62
28	0.5317	0.5340	0.5362	0.5384	0.5407	0.5430	0.5452	0.5475	0.5498	0.5520	61
29	0.5543	0.5566	0.5589	0.5612	0.5635	0.5658	0.5681	0.5704	0.5727	0.5750	60°
30°	0.5774	0.5797	0.5820	0.5844	0.5867	0.5890	0.5914	0.5938	0.5961	0.5985	59
31	0.6009	0.6032	0.6056	0.6080	0.6104	0.6128	0.6152	0.6176	0.6200	0.6224	58
32	0.6249	0.6273	0.6297	0.6322	0.6346	0.6371	0.6395	0.6420	0.6445	0.6469	57
33	0.6494	0.6519	0.6544	0.6569	0.6594	0.6619	0.6644	0.6669	0.6694	0.6720	56
34	0.6745	0.6771	0.6796	0.6822	0.6847	0.6873	0.6899	0.6924	0.6950	0.6976	55
35	0.7002	0.7028	0.7054	0.7080	0.7107	0.7133	0.7159	0.7186	0.7212	0.7239	54
36	0.7265	0.7292	0.7319	0.7346	0.7373	0.7400	0.7427	0.7454	0.7481	0.7508	53
37	0.7536	0.7563	0.7590	0.7618	0.7646	0.7673	0.7701	0.7729	0.7757	0.7785	52
38	0.7813	0.7841	0.7869	0.7898	0.7926	0.7954	0.7983	0.8012	0.8040	0.8069	51
39	0.8098	0.8127	0.8156	0.8185	0.8214	0.8243	0.8273	0.8302	0.8332	0.8361	50°
40°	0.8391	0.8421	0.8451	0.8481	0.8511	0.8541	0.8571	0.8601	0.8632	0.8662	49
41	0.8693	0.8724	0.8754	0.8785	0.8816	0.8847	0.8878	0.8910	0.8941	0.8972	48
42	0.9004	0.9036	0.9067	0.9099	0.9131	0.9163	0.9195	0.9228	0.9260	0.9293	47
43	0.9325	0.9358	0.9391	0.9424	0.9457	0.9490	0.9523	0.9556	0.9590	0.9623	46
44	0.9657	0.9691	0.9725	0.9759	0.9793	0.9827	0.9861	0.9896	0.9930	0.9965	45
	°1.0	°0.9	°0.8	°0.7	°0.6	°0.5	°0.4	°0.3	°0.2	°0.1	Deg.

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Natural Tangents and Cotangents—*Concluded*

Deg.	°0.0	°0.1	°0.2	°0.3	°0.4	°0.5	°0.6	°0.7	°0.8	°0.9	
45	1.0000	1.0035	1.0070	1.0105	1.0141	1.0176	1.0212	1.0247	1.0283	1.0319	44
46	1.0355	1.0392	1.0428	1.0464	1.0501	1.0538	1.0575	1.0612	1.0649	1.0686	43
47	1.0724	1.0761	1.0799	1.0837	1.0875	1.0913	1.0951	1.0990	1.1028	1.1067	42
48	1.1106	1.1145	1.1184	1.1224	1.1263	1.1303	1.1343	1.1383	1.1423	1.1463	41
49	1.1504	1.1544	1.1585	1.1626	1.1667	1.1708	1.1750	1.1792	1.1833	1.1875	40°
50°	1.1918	1.1960	1.2002	1.2045	1.2088	1.2131	1.2174	1.2218	1.2261	1.2305	39
51	1.2349	1.2393	1.2437	1.2482	1.2527	1.2572	1.2617	1.2662	1.2708	1.2753	38
52	1.2799	1.2846	1.2892	1.2938	1.2985	1.3032	1.3079	1.3127	1.3175	1.3223	37
53	1.3270	1.3319	1.3367	1.3416	1.3465	1.3514	1.3564	1.3613	1.3663	1.3713	36
54	1.3764	1.3814	1.3865	1.3916	1.3968	1.4019	1.4071	1.4124	1.4176	1.4229	35
55	1.4281	1.4335	1.4388	1.4442	1.4496	1.4550	1.4605	1.4659	1.4715	1.4770	34
56	1.4826	1.4882	1.4938	1.4994	1.5051	1.5108	1.5166	1.5224	1.5282	1.5340	33
57	1.5399	1.5458	1.5517	1.5577	1.5637	1.5697	1.5757	1.5818	1.5880	1.5941	32
58	1.6003	1.6066	1.6128	1.6191	1.6255	1.6319	1.6383	1.6447	1.6512	1.6577	31
59	1.6643	1.6709	1.6775	1.6842	1.6909	1.6977	1.7045	1.7113	1.7182	1.7251	30°
60°	1.7321	1.7391	1.7461	1.7532	1.7603	1.7675	1.7747	1.7820	1.7893	1.7966	29
61	1.8040	1.8115	1.8190	1.8265	1.8341	1.8418	1.8495	1.8572	1.8650	1.8728	28
62	1.8807	1.8887	1.8967	1.9047	1.9128	1.9210	1.9292	1.9375	1.9458	1.9542	27
63	1.9626	1.9711	1.9797	1.9883	1.9970	2.0057	2.0145	2.0233	2.0323	2.0413	26
64	2.0503	2.0594	2.0686	2.0778	2.0872	2.0965	2.1060	2.1155	2.1251	2.1348	25
65	2.1445	2.1543	2.1642	2.1742	2.1842	2.1943	2.2045	2.2148	2.2251	2.2355	24
66	2.2460	2.2566	2.2673	2.2781	3.2889	2.2998	2.3109	2.3220	2.3332	2.3445	23
67	2.3559	2.3673	2.3789	2.3906	2.4023	2.4142	2.4262	2.4383	2.4504	2.4627	22
68	2.4751	2.4876	2.5002	2.5129	2.5257	2.5386	2.5517	2.5649	2.5782	2.5916	21
69	2.6051	2.6187	2.6325	2.6464	2.6605	2.6746	2.6889	2.7034	2.7179	2.7326	20°
70°	2.7475	2.7625	2.7776	2.7929	2.8083	2.8239	2.8397	2.8556	2.8716	2.8878	19
71	2.9042	2.9208	2.9375	2.9544	2.9714	2.9887	3.0061	3.0237	2.0415	3.0595	18
72	3.0777	3.0961	3.1146	3.1334	3.1524	2.1716	3.1910	3.2106	3.2305	3.2506	17
73	3.2709	3.2914	3.3122	3.3332	3.3544	3.3759	3.3977	3.4197	3.4420	3.4646	16
74	3.4874	3.5105	3.5339	3.5576	3.5816	3.6059	3.6305	3.6554	3.6806	3.7062	15
75	3.7321	3.7583	3.7848	3.8118	3.8391	3.8667	3.8947	3.9232	3.9520	3.9812	14
76	4.0108	4.0408	4.0713	4.1022	4.1335	4.1653	4.1976	4.2303	4.2635	4.2972	13
77	4.3315	4.3662	4.4015	4.4374	4.4737	4.5107	4.5483	4.5864	4.6252	4.6646	12
78	4.7046	4.7453	4.7867	4.8288	4.8716	4.9152	4.9594	5.0045	5.0504	5.0970	11
79	5.1446	5.1929	5.2422	5.2924	5.3435	5.3955	5.4486	5.5026	5.5578	5.6140	10°
80°	5.6713	5.7297	5.7894	5.8502	5.9124	5.9758	6.0405	6.1066	6.1742	6.2432	9
81	6.3138	6.3859	6.4596	6.5350	6.6122	6.6912	6.7720	6.8548	6.9395	7.0264	8
82	7.1154	7.2066	7.3002	7.3962	7.4947	7.5958	7.6996	7.8062	7.9158	8.0285	7
83	8.1443	8.2636	8.3863	8.5126	8.6427	8.7769	8.9152	9.0579	9.2052	9.3572	6
84	9.5144	9.677	9.845	10.02	10.20	10.39	10.58	10.78	10.99	11.20	5
85	11.43	11.66	11.91	12.16	12.43	12.71	13.00	13.30	13.62	13.95	4
86	14.30	14.67	15.06	15.46	15.89	16.35	16.83	17.34	17.89	18.46	3
87	19.08	19.74	20.45	21.20	22.02	22.90	23.86	24.90	26.03	27.27	2
88	28.64	30.14	31.82	33.69	35.80	38.19	40.92	44.07	47.74	52.08	1
89	57.29	63.66	71.62	81.85	95.49	114.6	143.2	191.0	286.5	573.0	0°
	°1.0	°0.9	°0.8	°0.7	°0.6	°0.5	°0.4	°0.3	°0.2	°0.1	Deg.

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155. Logarithms of Numbers

N	0	1	2	3	4	5	6	7	8	9
10	0000	0043	0086	0128	0170	0212	0253	0294	0334	0374
11	0414	0453	0492	0531	0569	0607	0645	0682	0719	0755
12	0792	0828	0864	0899	0934	0969	1004	1038	1072	1106
13	1139	1173	1206	1239	1271	1303	1335	1367	1399	1430
14	1461	1492	1523	1553	1584	1614	1644	1673	1703	1732
15	1761	1790	1818	1847	1875	1903	1931	1959	1987	2014
16	2041	2068	2095	2122	2148	2175	2201	2227	2253	2279
17	2304	2330	2355	2380	2405	2430	2455	2480	2504	2529
18	2553	2577	2601	2625	2648	2672	2695	2718	2742	2765
19	2788	2810	2833	2856	2878	2900	2923	2945	2967	2989
20	3010	3032	3054	3075	3096	3118	3139	3160	3181	3201
21	3222	3243	3263	3284	3304	3324	3345	3365	3385	3404
22	3424	3444	3464	3483	3502	3522	3541	3560	3579	3598
23	3617	3636	3655	3674	3692	3711	3729	3747	3766	3784
24	3802	3820	3838	3856	3874	3892	3909	3927	3945	3962
25	3979	3997	4014	4031	4048	4065	4082	4099	4116	4133
26	4150	4166	4183	4200	4216	4232	4249	4265	4281	4298
27	4314	4330	4346	4362	4378	4393	4409	4425	4440	4456
28	4472	4487	4502	4518	4533	4548	4564	4579	4594	4609
29	4624	4639	4654	4669	4683	4698	4713	4728	4742	4757
30	4771	4786	4800	4814	4829	4843	4857	4871	4886	4900
31	4914	4928	4942	4955	4969	4983	4997	5011	5024	5038
32	5051	5065	5079	5092	5105	5119	5132	5145	5159	5172
33	5185	5198	5211	5224	5237	5250	5263	5276	5289	5302
34	5315	5328	5340	5353	5366	5378	5391	5403	5416	5428
35	5441	5453	5465	5478	5490	5502	5514	5527	5539	5551
36	5563	5575	5587	5599	5611	5623	5635	5647	5658	5670
37	5682	5694	5705	5717	5729	5740	5752	5763	5775	5786
38	5798	5809	5821	5832	5843	5855	5866	5877	5888	5899
39	5911	5922	5933	5944	5955	5966	5977	5988	5999	6010
40	6021	6031	6042	6053	6064	6075	6085	6096	6107	6117
41	6128	6138	6149	6160	6170	6180	6191	6201	6212	6222
42	6232	6243	6253	6263	6274	6284	6294	6304	6314	6325
43	6335	6345	6355	6365	6375	6385	6395	6405	6415	6425
44	6435	6444	6454	6464	6474	6484	6493	6503	6513	6522
45	6532	6542	6551	6561	6571	6580	6590	6599	6609	6618
46	6628	6637	6646	6656	6665	6675	6684	6693	6702	6712
47	6721	6730	6739	6749	6758	6767	6776	6785	6794	6803
48	6812	6821	6830	6839	6848	6857	6866	6875	6884	6893
49	6902	6911	6920	6928	6937	6946	6955	6964	6972	6981
50	6990	6998	7007	7016	7024	7033	7042	7050	7059	7067
51	7076	7084	7093	7101	7110	7118	7126	7135	7143	7152
52	7160	7168	7177	7185	7193	7202	7210	7218	7226	7235
53	7243	7251	7259	7267	7275	7284	7292	7300	7308	7316
54	7324	7332	7340	7348	7356	7364	7372	7380	7388	7396

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Logarithms of Numbers.—*Concluded*

N	0	1	2	3	4	5	6	7	8	9
55	7404	7412	7419	7427	7435	7443	7451	7459	7466	7474
56	7482	7490	7497	7505	7513	7520	7528	7536	7543	7551
57	7559	7566	7574	7582	7589	7597	7604	7612	7619	7627
58	7634	7642	7649	7657	7664	7672	7679	7686	7694	7701
59	7709	7716	7723	7731	7738	7745	7752	7760	7767	7774
60	7782	7789	7796	7803	7810	7818	7825	7832	7839	7846
61	7853	7860	7868	7875	7882	7889	7896	7903	7910	7917
62	7924	7931	7938	7945	7952	7959	7966	7973	7980	7987
63	7993	8000	8007	8014	8021	8028	8035	8041	8048	8055
64	8062	8069	8075	8082	8089	8096	8102	8109	8116	8122
65	8129	8136	8142	8149	8156	8162	8169	8176	8182	8189
66	8195	8202	8209	8215	8222	8228	8235	8241	8248	8254
67	8261	8267	8274	8280	8287	8293	8299	8306	8312	8319
68	8325	8331	8338	8344	8351	8357	8363	8370	8376	8383
69	8388	8395	8401	8407	8414	8420	8426	8432	8439	8445
70	8451	8457	8463	8470	8476	8482	8488	8494	8500	8506
71	8513	8519	8525	8531	8537	8543	8549	8555	8561	8567
72	8573	8579	8585	8591	8597	8603	8609	8615	8621	8627
73	8633	8639	8645	8651	8657	8663	8669	8675	8681	8686
74	8692	8698	8704	8710	8716	8722	8727	8733	8739	8745
75	8751	8756	8762	8768	8774	8779	8785	8791	8797	8802
76	8808	8814	8820	8825	8831	8837	8842	8848	8854	8859
77	8865	8871	8876	8882	8887	8893	8899	8904	8910	8915
78	8921	8927	8932	8938	8943	8949	8954	8960	8965	8971
79	8976	8982	8987	8993	8998	9004	9009	9015	9020	9025
80	9031	9036	9042	9047	9053	9058	9063	9069	9074	9079
81	9085	9090	9096	9101	9106	9112	9117	9122	9128	9133
82	9138	9143	9149	9154	9159	9165	9170	9175	9180	9186
83	9191	9196	9201	9206	9212	9217	9222	9227	9232	9238
84	9243	9248	9253	9258	9263	9269	9274	9279	9284	9289
85	9294	9299	9304	9309	9315	9320	9325	9330	9335	9340
86	9345	9350	9355	9360	9365	9370	9375	9380	9385	9390
87	9395	9400	9405	9410	9415	9420	9425	9430	9435	9440
88	9445	9450	9455	9460	9465	9469	9474	9479	9484	9489
89	9494	9499	9504	9509	9513	9518	9523	9528	9533	9538
90	9542	9547	9552	9557	9562	9566	9571	9576	9581	9586
91	9590	9595	9600	9605	9609	9614	9619	9624	9628	9633
92	9638	9643	9647	9652	9657	9661	9666	9671	9675	9680
93	9685	9689	9694	9699	9703	9708	9713	9717	9722	9727
94	9731	9736	9741	9745	9750	9754	9759	9763	9768	9773
95	9777	9782	9786	9791	9795	9800	9805	9809	9814	9818
96	9823	9827	9832	9836	9841	9845	9850	9854	9859	9863
97	9868	9872	9877	9881	9886	9890	9894	9899	9903	9908
98	9912	9917	9921	9926	9930	9934	9939	9943	9948	9952
99	9956	9961	9965	9969	9974	9978	9983	9987	9991	9996

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156. Hyperbolic Logarithms

y	0	1	2	3	4	5	6	7	8	9
0	$-\infty$	0.0000	0.6931	1.0986	1.3863	1.6094	1.7918	1.9459	2.0794	2.1972
10	2.3026	2.3979	2.4849	2.5649	2.6391	2.7081	2.7726	2.8332	2.8904	2.9444
20	2.9957	3.0445	3.0910	3.1355	3.1781	3.2189	3.2581	3.2958	3.3322	3.3673
30	3.4012	3.4340	3.4657	3.4965	3.5264	3.5553	3.5835	3.6109	3.6376	3.6636
40	3.6889	3.7136	3.7377	3.7612	3.7842	3.8067	3.8286	3.8501	3.8712	3.8918
50	3.9120	3.9318	3.9512	3.9703	3.9890	4.0073	4.0254	4.0431	4.0604	4.0775
60	4.0943	4.1109	4.1271	4.1431	4.1589	4.1744	4.1897	4.2047	4.2195	4.2341
70	4.2485	4.2627	4.2767	4.2905	4.3041	4.3175	4.3307	4.3438	4.3567	4.3694
80	4.3820	4.3944	4.4067	4.4188	4.4308	4.4427	4.4543	4.4659	4.4773	4.4886
90	4.4998	4.5109	4.5218	4.5326	4.5433	4.5539	4.5643	4.5747	4.5850	4.5951
100	4.6052	4.6151	4.6250	4.6347	4.6444	4.6540	4.6634	4.6728	4.6821	4.6913
110	4.7005	4.7095	4.7185	4.7274	4.7362	4.7449	4.7536	4.7622	4.7707	4.7791
120	4.7875	4.7958	4.8040	4.8122	4.8203	4.8283	4.8363	4.8442	4.8520	4.8598
130	4.8675	4.8752	4.8828	4.8903	4.8978	4.9053	4.9127	4.9200	4.9273	4.9345
140	4.9416	4.9488	4.9558	4.9628	4.9698	4.9767	4.9836	4.9904	4.9972	5.0039
150	5.0106	5.0173	5.0239	5.0304	5.0370	5.0434	5.0499	5.0562	5.0626	5.0689
160	5.0752	5.0814	5.0876	5.0938	5.0999	5.1059	5.1120	5.1180	5.1240	5.1299
170	5.1358	5.1417	5.1475	5.1533	5.1591	5.1648	5.1705	5.1761	5.1818	5.1874
180	5.1930	5.1985	5.2040	5.2095	5.2149	5.2204	5.2257	5.2311	5.2364	5.2417
190	5.2470	5.2523	5.2575	5.2627	5.2679	5.2730	5.2781	5.2832	5.2883	5.2933
200	5.2983	5.3033	5.3083	5.3132	5.3181	5.3230	5.3279	5.3327	5.3375	5.3423
210	5.3471	5.3519	5.3566	5.3613	5.3660	5.3706	5.3753	5.3799	5.3845	5.3891
220	5.3936	5.3982	5.4027	5.4072	5.4116	5.4161	5.4205	5.4250	5.4293	5.4337
230	5.4381	5.4424	5.4467	5.4510	5.4553	5.4596	5.4638	5.4681	5.4723	5.4765
240	5.4806	5.4848	5.4889	5.4931	5.4972	5.5013	5.5053	5.5094	5.5134	5.5175
250	5.5215	5.5255	5.5294	5.5334	5.5373	5.5413	5.5452	5.5491	5.5530	5.5568
260	5.5607	5.5645	5.5683	5.5722	5.5759	5.5797	5.5835	5.5872	5.5910	5.5947
270	5.5984	5.6021	5.6058	5.6095	5.6131	5.6168	5.6204	5.6240	5.6276	5.6312
280	5.6348	5.6384	5.6419	5.6454	5.6490	5.6525	5.6560	5.6595	5.6630	5.6664
290	5.6699	5.6733	5.6768	5.6802	5.6836	5.6870	5.6904	5.6937	5.6971	5.7004
300	5.7038	5.7071	5.7104	5.7137	5.7170	5.7203	5.7236	5.7268	5.7301	5.7333
310	5.7366	5.7398	5.7430	5.7462	5.7494	5.7526	5.7557	5.7589	5.7621	5.7652
320	5.7683	5.7714	5.7746	5.7777	5.7807	5.7838	5.7869	5.7900	5.7930	5.7961
330	5.7991	5.8021	5.8051	5.8081	5.8111	5.8141	5.8171	5.8201	5.8230	5.8260
340	5.8289	5.8319	5.8348	5.8377	5.8406	5.8435	5.8464	5.8493	5.8522	5.8551
350	5.8579	5.8608	5.8636	5.8665	5.8693	5.8721	5.8749	5.8777	5.8805	5.8833
360	5.8861	5.8889	5.8916	5.8944	5.8972	5.8999	5.9026	5.9054	5.9081	5.9108
370	5.9135	5.9162	5.9189	5.9216	5.9243	5.9269	5.9296	5.9322	5.9349	5.9375
380	5.9402	5.9428	5.9454	5.9480	5.9506	5.9532	5.9558	5.9584	5.9610	5.9636
390	5.9661	5.9687	5.9713	5.9738	5.9764	5.9789	5.9814	5.9839	5.9865	5.9890
400	5.9915	5.9940	5.9965	5.9989	6.0014	6.0039	6.0064	6.0088	6.0113	6.0137
410	6.0162	6.0186	6.0210	6.0234	6.0259	6.0283	6.0307	6.0331	6.0355	6.0379
420	6.0403	6.0426	6.0450	6.0474	6.0497	6.0521	6.0544	6.0568	6.0591	6.0615
430	6.0638	6.0661	6.0684	6.0707	6.0730	6.0753	6.0776	6.0799	6.0822	6.0845
440	6.0868	6.0890	6.0913	6.0936	6.0958	6.0981	6.1003	6.1026	6.1048	6.1070
450	6.1092	6.1115	6.1137	6.1159	6.1181	6.1203	6.1225	6.1247	6.1269	6.1291
460	6.1312	6.1334	6.1356	6.1377	6.1399	6.1420	6.1442	6.1463	6.1485	6.1506
470	6.1527	6.1549	6.1570	6.1591	6.1612	6.1633	6.1654	6.1675	6.1696	6.1717
480	6.1738	6.1759	6.1779	6.1800	6.1821	6.1841	6.1862	6.1883	6.1903	6.1924
490	6.1944	6.1964	6.1985	6.2005	6.2025	6.2046	6.2066	6.2086	6.2106	6.2126

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Hyperbolic Logarithms.—*Concluded*

N	0	1	2	3	4	5	6	7	8	9
500	6.2146	6.2166	6.2186	6.2206	6.2226	6.2246	6.2265	6.2285	6.2305	6.2324
510	6.2344	6.2364	6.2383	6.2403	6.2422	6.2442	6.2461	6.2480	6.2500	6.2519
520	6.2538	6.2558	6.2577	6.2596	6.2615	6.2634	6.2653	6.2672	6.2691	6.2710
530	6.2729	6.2748	6.2766	6.2785	6.2804	6.2823	6.2841	6.2860	6.2879	6.2897
540	6.2916	6.2934	6.2953	6.2971	6.2989	6.3008	6.3026	6.3044	6.3063	6.3081
550	6.3099	6.3117	6.3135	6.3154	6.3172	6.3190	6.3208	6.3226	6.3244	6.3261
560	6.3279	6.3297	6.3315	6.3333	6.3351	6.3368	6.3386	6.3404	6.3421	6.3439
570	6.3456	6.3474	6.3491	6.3509	6.3526	6.3544	6.3561	6.3578	6.3596	6.3613
580	6.3630	6.3648	6.3665	6.3682	6.3699	6.3716	6.3733	6.3750	6.3767	6.3784
590	6.3801	6.3818	6.3835	6.3852	6.3869	6.3886	6.3902	6.3919	6.3936	6.3953
600	6.3969	6.3986	6.4003	6.4019	6.4036	6.4052	6.4069	6.4085	6.4102	6.4118
610	6.4135	6.4151	6.4167	6.4184	6.4200	6.4216	6.4232	6.4249	6.4265	6.4281
620	6.4297	6.4313	6.4329	6.4345	6.4362	6.4378	6.4394	6.4409	6.4425	6.4441
630	6.4457	6.4473	6.4489	6.4505	6.4520	6.4536	6.4552	6.4568	6.4583	6.4599
640	6.4615	6.4630	6.4646	6.4661	6.4677	6.4693	6.4708	6.4723	6.4739	6.4754
650	6.4770	6.4785	6.4800	6.4816	6.4831	6.4846	6.4862	6.4877	6.4892	6.4907
660	6.4922	6.4938	6.4953	6.4968	6.4983	6.4998	6.5013	6.5028	6.5043	6.5058
670	6.5073	6.5088	6.5103	6.5117	6.5132	6.5147	6.5162	6.5177	6.5191	6.5206
680	6.5221	6.5236	6.5250	6.5265	6.5280	6.5294	6.5309	6.5323	6.5338	6.5352
690	6.5367	6.5381	6.5396	6.5410	6.5425	6.5439	6.5453	6.5468	6.5482	6.5497
700	6.5511	6.5525	6.5539	6.5554	6.5568	6.5582	6.5596	6.5610	6.5624	6.5639
710	6.5653	6.5667	6.5681	6.5695	6.5709	6.5723	6.5737	6.5751	6.5765	6.5779
720	6.5793	6.5806	6.5820	6.5834	6.5848	6.5862	6.5876	6.5889	6.5903	6.5917
730	6.5930	6.5944	6.5958	6.5971	6.5985	6.5999	6.6012	6.6026	6.6039	6.6053
740	6.6067	6.6080	6.6093	6.6107	6.6120	6.6134	6.6147	6.6161	6.6174	6.6187
750	6.6201	6.6214	6.6227	6.6241	6.6254	6.6267	6.6280	6.6294	6.6307	6.6320
760	6.6333	6.6346	6.6359	6.6373	6.6386	6.6399	6.6412	6.6425	6.6438	6.6451
770	6.6464	6.6477	6.6490	6.6503	6.6516	6.6529	6.6542	6.6554	6.6567	6.6580
780	6.6593	6.6606	6.6619	6.6631	6.6644	6.6657	6.6670	6.6682	6.6695	6.6708
790	6.6720	6.6733	6.6746	6.6758	6.6771	6.6783	6.6796	6.6809	6.6821	6.6834
800	6.6846	6.6859	5.6871	6.6884	6.6896	6.6908	6.6921	6.6933	6.6946	6.6958
810	6.6970	6.6983	6.6995	6.7007	6.7020	6.7032	6.7044	6.7056	6.7069	6.7081
820	6.7093	6.7105	6.7117	6.7130	6.7142	6.7154	6.7166	6.7178	6.7190	6.7203
830	6.7214	6.7226	6.7238	6.7250	6.7262	6.7274	6.7286	6.7298	6.7310	6.7322
840	6.7334	6.7346	6.7358	6.7370	6.7382	6.7393	6.7405	6.7417	6.7429	6.7441
850	6.7452	6.7464	6.7476	6.7488	6.7499	6.7511	6.7523	6.7534	6.7546	6.7558
860	6.7569	6.7581	6.7593	6.7604	6.7616	6.7627	6.7639	6.7650	6.7662	6.7673
870	6.7685	6.7696	6.7708	6.7719	6.7731	6.7742	6.7754	6.7765	6.7776	6.7788
880	6.7799	6.7811	6.7822	6.7833	6.7845	6.7856	6.7867	5.7878	6.7890	6.7901
890	6.7912	6.7923	6.7935	6.7946	6.7957	6.7968	6.7979	6.7991	6.8002	6.8013
900	6.8024	6.8035	6.8046	6.8057	6.8068	6.8079	6.8090	6.8101	6.8112	6.8123
910	6.8134	6.8145	6.8156	6.8167	6.8178	6.8189	6.8200	6.8211	6.8222	6.8233
920	6.8244	6.8255	6.8265	6.8276	6.8287	6.8298	6.8309	6.8320	6.8330	6.8341
930	6.8352	6.8363	6.8373	6.8384	6.8395	6.8405	6.8416	6.8427	6.8437	6.8448
940	6.8459	6.8469	6.8480	6.8491	6.8501	6.8512	6.8522	6.8533	6.8544	6.8554
950	6.8565	6.8575	6.8586	6.8596	6.8607	6.8617	6.8628	6.8638	6.8648	6.8659
960	6.8669	6.8680	6.8690	6.8701	6.8711	6.8721	6.8732	6.8742	6.8752	6.8763
970	6.8773	6.8783	6.8794	6.8804	6.8814	6.8824	6.8835	6.8845	6.8855	6.8865
980	6.8876	6.8886	6.8896	6.8906	6.8916	6.8926	6.8937	6.8947	6.8957	6.8967
990	6.8977	6.8987	6.8997	6.9007	6.9017	6.9027	6.9037	6.9047	6.9057	6.9067

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SECTION 2

ELECTRIC AND MAGNETIC CIRCUITS

BY VLADIMIR KARAPETOFF,

Professor of Electrical Engineering, Cornell University, Fellow, American Institute of Electrical Engineers

CONTENTS.

(*Numbers refer to Paragraphs*)

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SECTION 2

ELECTRIC AND MAGNETIC CIRCUITS

ELECTRIC POTENTIAL

1. The cause of an electric current in a circuit is termed the **electromotive force** or **voltage.** The latter name is derived from the practical unit of electromotive force called the volt. The current between two points in a circuit is due to a different electric state or "potential" at each point; for this reason the electromotive force or voltage is sometimes called the **difference of potential.**

2. The electric energy (W) developed or absorbed by an electric circuit may be considered due to the actual flow of an incompressible something which we call electricity. From this point of view, the quantity of electricity Q which is transferred between two points of the circuit is the quantity factor of the energy, while the difference of potential, or the voltage E between the same points, is the intensity factor of the energy ; or

$$W = QE. \tag{1}$$

When Q is in coulombs, and E in volts, W is in joules (watt-seconds). Hence, electromotive force or voltage may also be defined as electrical energy developed or work done per unit quantity of electricity.

3. Electric Power.—Dividing both sides of the preceding equation by the time which it takes for the quantity Q to flow through a cross-section of the circuit, we get

$$P = IE, \tag{2}$$

where P is the power, and I the rate of flow or the current. The e.m.f. can thus be defined as the power developed per unit of current.

4. The principal sources of electromotive force or difference of potential are the following:

(a) Electromagnetic induction (see Par. **36**);
(b) Contact of dissimilar substances (see Par. **5**);
(c) Thermo-electric action (see Par. **5**);
(d) Chemical action (Sec. 20);
(e) Friction between dissimilar substances (see Sec. 22).

In the light of the modern electrical theory, all these phenonema, with the exception of (a), appear to be but special cases of the general contact action.

5. In a circuit made up of several substances, a difference of potential (e.m.f.) exists at each junction of two unlike substances. However, from the law of conservation of energy it follows that unless the circuit contain a source of energy, the resultant e.m.f. in the circuit must be zero and no current can be established. This phenomenon also takes place in circuits made up of a single substance whenever the substance is not physically and chemically homogeneous. The following are the principal cases of thermal and contact action:

(a) **Seebeck effect.** In a closed circuit consisting of two different metals, if the two junctions are kept at different temperatures, a permanent current will flow. Thus, if one junction of a copper-iron circuit be kept in melting ice and the other in boiling water, it will be found that a current passes from copper to iron across the hot junction. If, however, the temperature of the hot junction be raised gradually, the e.m.f. in the circuit slowly reaches a maximum, then sinks to zero, and finally is reversed.

(b) **Peltier effect.** When a current is passed across the junction between two different metals, an evolution or an absorption of heat takes place. This effect is different from the evolution of heat (i^2r), due to the resistance of the junction, and is reversible, heat being evolved when the current

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passes one way across the junction and absorbed when the current passes in the other direction. There is a definite relation between the direction of the thermo-electric current and the sign of the Peltier effect. If a current be forced across a junction in the same direction as the thermo-electric current flows at the hot junction, the junction will be cooled, that is, heat will be absorbed. Conversely, a current passing in the normal direction across the cold junction of a thermo-electric circuit evolves heat. In general, then, a thermo-electric current absorbs heat at the hot junction and gives up heat at the cold junction. Therefore, a current produced in the same direction by external means must cool off the junction which serves as the "hot" junction and warm up the "cold" junction.

(c) **Thomson effect.** In a copper bar, heat is carried with the electric current when it flows from hot regions to cold ones; on the other hand, when the current flows from cold regions to hot ones, these hot parts of the bar are cooled. In iron these effects are reversed. The conductor may be thought of as composed of a number of little elements of volume, at the junctions between which occur reversible heat effects, similar to Peltier effects at the junctions between different metals.

(d) **Volta effect, or contact electrification.** When pieces of various materials are brought in contact, an e.m.f. is developed between them. Thus, in the case of zinc and copper, zinc becomes charged positively and copper negatively. According to the electron theory, different substances possess different tendencies to give up their negatively charged corpuscles. Zinc gives them up very easily; therefore a number of negatively charged particles pass from it to copper. Measurable e.m.fs. are observed even between two pieces of the same substance, having different structures; for instance between a piece of cast copper and electrolytic copper. Frictional electricity is explained in a similar way, only a more intimate contact is necessary where the conductivities of the substances are small.

6. **Literature references.** For a detailed treatment, curves and mathematical theory of thermo-electric and contact phenomena see Maxwell, J. C., "Electricity and Magnetism," Vol. I, Arts. 246 *et seq.*; Encyclopedia Britannica, under "Thermo-electricity"; Whetham, W. C. D., "The Theory of Experimental Electricity," Chap. 6; Brooks and Poyser, "Magnetism and Electricity," Chap. 28. For an explanation of thermo-electric effects in the language of the electron theory see Fournier d'Albee, "The Electron Theory," Chap. 5; Thomson, J. J., "The Corpuscular Theory of Matter," pp. 73 and 97; Campbell, N. R., "Modern Electrical Theory," pp. 118–124.

7. **The value of the e.m.f. at a junction of unlike substances** depends upon the kind of substances, and is approximately proportional to the temperature. The e.m.f. generated in this way can be utilised as a measure of temperature. For temperature rises up to 200 deg. cent.

$$e = k_1 t + k_2 t^2, \tag{3}$$

and for temperature rises above 200 deg. cent.

$$\log e = k_3 \log t + k_4 \tag{4}$$

A more general formula is

$$e = a + bt + ct^2 \tag{5}$$

The quantities k_1, k_2, k_3, k_4, a, b and c are constants.

8. **Thermocouples and batteries.** In order to utilise these contact e.m.fs., means must be devised to supply energy to the system continuously. There are two ways of doing this, namely, by heat and by chemical reaction. The thermocouple is an example of the former, and the battery an example of the latter. For further discussion of thermocouples see Sec. 3. Batteries are treated in Sec. 20.

ELECTRIC CURRENTS

9. **An electric current is defined** as the rate of flow of electricity, or the quantity of electricity which flows through a cross-section of the circuit per unit time. If the current I is steady, then

$$I = \frac{Q}{T}, \tag{6}$$

If Q is the quantity of electricity in coulombs, and T the time in seconds,

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the current I is in amperes. When the rate of flow is non-uniform, the instantaneous current is

$$i = \frac{\partial q}{\partial t}; \tag{7}$$

for a classification of electric currents see the Standardisation Rules of the American Institute of Electrical Engineers, Sec. 24.

10. Steady and transient states. An electric circuit may be in a steady or in a transient state. When a current is continuous, or when it varies periodically between the same limits and according to the same law, the circuit is said to be in a **steady state**. For instance, the circuit of an alternator is steady as long as the load, speed and field excitation are kept constant. The same circuit is in a transient state when the load is switched on or off, or when it is varied in such a way that the same conditions do not repeat themselves periodically. A transient current may be periodic, for instance in a rectifier, in which cycles follow in such rapid succession that the current is very different from the permanent value which it would gradually assume.

11. A direct current given out by a chemical battery is constant in value, or **continuous**, when the load is constant. A current delivered under the same conditions by an electric generator or a rectifier is **pulsating**, that is, it varies periodically due to a finite number of commutator segments.

12. An alternating current may vary according to the **simple sine law** (Par. **152**), or according to a **more complicated periodic law**. In the latter case the current may be resolved, for purposes of theory and analysis, into a fundamental sine wave, and sine waves of higher frequencies (Par. **209**). Sometimes a complex alternating current or voltage is replaced for practical purposes by an equivalent sine-wave.

13. Transient currents may be oscillating or non-oscillating, according to the conditions in the circuit. Oscillations are due to periodic transformations of the electrostatic energy stored in the dielectric into the electromagnetic energy of the magnetic flux linking with the current. During these transformations part of the energy is converted into the Joulean (i^2r) heat in the conductors and in surrounding metallic objects including the iron of the magnetic circuit. Part of the energy is also converted into the heat caused by magnetic and dielectric hysteresis. The oscillations are thus damped out, and their amplitude decreases. When the conditions are particularly favorable for the conversion into heat (high resistance in series, or low resistance in parallel), both the electrostatic and the electromagnetic energy are directly converted into heat, instead of being partly converted into one another. This conversion into heat is an irreversible phenomenon, so that in this case the current is non-oscillating, but gradually reaches its final value. When it is desired to maintain oscillations as long as possible (wireless telegraphy) the series resistance must be kept down as low as possible. When oscillations are harmful (switching in long cables or transmission lines), extra resistance is temporarily connected in the circuit.

14. Conductors and insulators. For practical purposes, materials used in electrical engineering are divided into conductors and insulators. A conducting material allows a continuous current to pass through it under the action of a continuous e.m.f. An insulator (more correctly called a **dielectric**) allows only a brief transient current which charges it electrostatically. This charge or displacement of electricity produces a counter-e.m.f. equal and opposite to the applied e.m.f., and the flow of current ceases. The division into conductors and dielectrics is not strictly correct, but is convenient for practical purposes. A substance may practically stop the flow of current when the applied voltage is sufficiently low, and at the same time be unsuitable as an insulator at high voltages. Some materials which are practically non-conducting at ordinary temperatures become good conductors when sufficiently heated. For numerical data and tables of conducting and insulating properties of the principal materials used in practice see Sec. 4.

15. The electronic theory of conduction. According to the modern electronic or corpuscular theory of electricity, there is an indivisible atom of negative electricity, called the **electron** or the **corpuscle**. Atoms of matter consist of one or more electrons and an unknown something which has the

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nature of positive electricity. A negatively charged particle of matter is one in which there are more electrons than necessary to neutralise its positive electricity. A positively electrified body is one which has lost some of the electrons it had in the neutral state.

16. **Metals and other solid conductors supposedly possess free or roaming electrons,** in addition to those associated with the molecules. These free electrons are in rapid motion as if they were the particles of a gas dissolved in the metal. When an e.m.f. is applied, each electron gains a component velocity which, on account of its negative charge, is in the opposite direction to the e.m.f. This drift of electrons is equivalent to a current. In their motion the electrons come in collision with the molecules and give up part of their momentum. This loss is supposed to account for the Joulean (i^2r) heat set free in all conductors. Also see Sec. 22.

17. **Electrolytes.** In liquids which are chemical compounds (electrolytes) the passage of an electric current is accompanied by a chemical decomposition. Atoms of metals and hydrogen travel through the liquid in the direction of the positive current, while oxygen and acid radicals travel against the positive current. Thus, while in solid conductors electricity travels across the matter, in electrolytes it travels with the matter. For details of electrolytic conduction see Sec. 19.

18. **Gases in the normal state conduct electricity only to a slight degree.** A gas may be put in the conducting state by different means, such as raising its temperature, drawing it from the neighborhood of flames, arcs, or glowing metals or from a space in which an electric discharge is passing, etc. This conductivity is due to electrons which form electrified particles mixed up with the gas (ions). The process by which a gas is made into a conductor is called the **ionization** of the gas. The movement of free electrons constitutes the current through the gas.* Also see Sec. 19.

CONTINUOUS-CURRENT CIRCUITS

19. **Ohm's law.** When the current in a conductor is steady and there are no electromotive forces within the conductor, the value of the current i is proportional to the voltage e between the terminals of the conductor, or

$$e = ri \tag{8}$$

where the coefficient of proportionality r is called the **resistance** of the conductor. The same law may be written in the form

$$i = ge \tag{9}$$

where the coefficient of proportionality $g = 1/r$ is called the **conductance** of the conductor. When the current is measured in amperes and the electromotive force in volts, the resistance r is in ohms and g is in mhos.

When there is a **counter-electromotive force** e_c **within the conductor,** Ohm's law becomes

$$e_t - e_c = ri, \tag{10}$$

or

$$i = g(e_t - e_c), \tag{11}$$

where e_t is the voltage between the terminals of the conductor.

20. **For cylindrical conductors** the resistance is proportional to the length l, and inversely proportional to the cross-section A, or

$$r = \rho \frac{l}{A}, \tag{12}$$

where the coefficient of proportionality ρ (rho) is called the **resistivity** (or specific resistance) of the material. For numerical values of ρ for various materials see Sec. 4.

The conductance of a cylindrical conductor is

$$g = \lambda \frac{A}{l}, \tag{13}$$

* For the original development of the electronic theory and its application to various electric and magnetic phenomena see numerous books and articles by Sir J. J. Thomson. A popular exposition of the results will be found in Fournier d'Albee's "The Electron Theory" and in a somewhat more advanced "Modern Electrical Theory" by N. R. Campbell and in "The Electron Theory of Matter" by O. W. Richardson.

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where λ (lambda) is called the **conductivity** of the material. Since $g = 1/$ the relation also holds, that

$$\lambda = \frac{1}{\rho}. \qquad (1$$

For the calculation of resistance of non-cylindrical conductors see t author's "Electric Circuit," Chap. III, and the references given there.

21. Temperature coefficient. The resistance of a conductor vari with the temperature according to a rather complicated law. The resistan of all metals and of practically all alloys increases with the temperatu The resistance of carbon and of electrolytes decreases with the temperatu For numerical values see Sec. 4. For many materials the variation of r sistance with the temperature can be represented by the relation

$$r_t = r_0(1 + \alpha t) \qquad (1.$$

where r_t is the resistance at t deg. cent., r_0 the resistance at 0 deg. cent., ar α (alpha) is called the temperature coefficient of the material. For numeric values of α for various materials see Sec. 4. When the resistance of a materi increases with the temperature, α is positive; otherwise it is negative. F other formulæ see Sec. 4.

22. Resistances and conductances in series. When two or mo resistances are connected in series the equivalent resistance of the combin tion is equal to the sum of the resistances of the individual resistors, or

$$r_{eq} = r_1 + r_2 + \text{etc.} \qquad (1$$

When conductances are connected in series, the equivalent conductan g_{eq} is determined from the relation

$$\frac{1}{g_{eq}} = \frac{1}{g_1} + \frac{1}{g_2} + \text{etc.}, \qquad (1$$

in other words, when two or more conductors are connected in series, t reciprocal of the equivalent conductance is equal to the sum of the reciproca of the individual conductances.

23. When resistances are connected in parallel, the equivalent re sistance r_{eq} is determined from the relation

$$\frac{1}{r_{eq}} = \frac{1}{r_1} + \frac{1}{r_2} + \text{etc.} \qquad (18$$

or simply

$$g_{eq} = g_1 + g_2 + \text{etc.} \qquad (19$$

24. The simple rule is: Resistances are added when in series; con ductances are added when in parallel. In the case often met in practic when two resistances are connected in parallel

$$r_{eq} = \frac{r_1 r_2}{r_1 + r_2}. \qquad (20)$$

25. Series-parallel circuits. In a combination like the one shown in Fig. 1, where some of the resistances are in series, some in parallel, and where it is required to find the equivalent resistance between A and B, the problem is solved step by step, by combining the resistances in series, converting them into conductances and adding them with other conductances in parallel. For instance, in the cas shown in Fig. 1 begin by combining the resistances r_2 and R into one, an determine the corresponding conductance

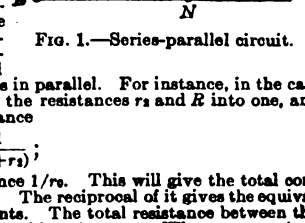


FIG. 1.—Series-parallel circuit.

$$\frac{1}{(R + r_2)},$$

add this conductance to the conductance $1/r_0$. This will give the total con ductance between the points M and N. The reciprocal of it gives the equiva lent resistance between the same points. The total resistance between th points A and B is found by adding r_1 to this resistance. When a network o conductors cannot be reduced to a series-parallel combination, the proble is solved as shown in Par. 29.

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16. Power and energy. When a steady current i flows through a conductor and the voltage across the terminals of the conductor is e, the power, or the energy per unit time, delivered to the conductor is

$$P = ei. \tag{21}$$

If the current is expressed in amperes and the potential in volts, the power P is in watts (joules per second). When the voltage and the current are variable, their instantaneous values being represented by e and i respectively, the preceding equation gives the instantaneous power, that is the instantaneous rate at which energy is being delivered to the conductor.

The total energy delivered to the conductor during a time t is

$$W = eit = eQ, \tag{22}$$

where Q is the total quantity of electricity (coulombs) which passed through the conductor. If Q is in coulombs (ampere-seconds), W is in joules (watt-seconds). When the voltage and the current are variable the total energy is expressed by

$$W = \int_{t_1}^{t_2} ei\,\partial t, \tag{23}$$

where the time interval is $t_2 - t_1$.

17. Joule's law. When the conductor contains ohmic resistance only and no counter-electromotive forces, we have $e = ri = i/g$, so that the power

$$P = i^2 r = \frac{i^2}{g} = \frac{e^2}{r} = e^2 g. \tag{24}$$

This expression is known as **Joule's law.**

18. If the conductor contains a counter-e.m.f., e_c, for instance, that of a motor or of a battery, **the power** is given by

$$P = e_t i = e_c i + i^2 r, \tag{25}$$

where e_t is the voltage across the terminals of the conductor. In this expression $e_c i$ is the useful power, and $i^2 r$ is the heat loss in the conductor. See Par. 19.

19. Kirchhoff's laws. In an arbitrary network of conductors (Fig. 2) with sources of continuous e.m.f. connected in one or more places, the distribution of the currents is such that two conditions are satisfied, namely,

$$\Sigma i = 0, \text{ and } \Sigma e = \Sigma ir. \tag{26}$$

The first equation refers to any junction point of three or more conductors and states the fact that as much current flows toward the junction as away from it, because electricity behaves like an incompressible fluid. In this equation all the currents which flow toward the junction are taken with the sign plus (+); all those which flow away from it with the sign minus (−), or *vice versa*. The second law refers to any closed circuit taken at random in the network. The voltages e are the local electromotive forces in such a circuit and the currents and the resistances refer to the individual conductors of the circuit. The directions of flow of the currents can be assumed arbitrarily to start with, and in writing the second equation one follows a selected circuit in a certain direction, clockwise or counter-clockwise, taking as positive the currents which flow in this direction and the e.m.fs. which tend to produce currents in the same direction. The currents and the voltages in the opposite direction are entered in the equation with the sign minus. For a given network of conductors the total number of equations of the first form is equal to the number of junction points less one; the number of equations of the second kind is equal to the number of *independent* closed paths in the network. The total number of equations of both kinds is equal to the number of unknown currents so that these currents can be

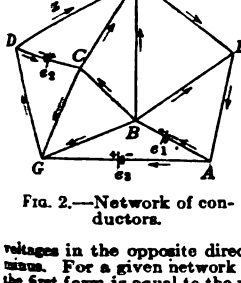


FIG. 2.—Network of conductors.

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determined by solving simultaneous equations. For an example of such equations see Par. **31** below.

30. Wheatstone bridge. The combination of six resistances shown in Fig. 3 is called the Wheatstone bridge. The resistances are denoted by $a, b, c, \alpha, \beta, \gamma$, the currents by $x, y, z, \xi, \eta, \zeta$. An electric battery of e.m.f. E is connected in the branch BC, and the value of a includes the internal resistance of the battery. In practice a galvanometer is usually connected in the branch OA, and α includes its resistance. When the four resistances b, c, β, γ, are so adjusted that no current flows through OA, the bridge is said to be balanced, and the condition holds that,

$$b\beta = c\gamma. \qquad (27)$$

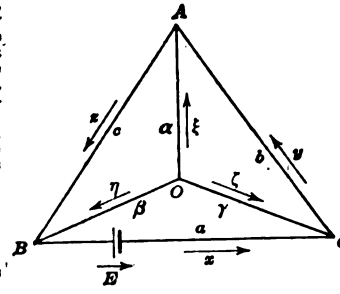


FIG. 3.—Wheatstone Bridge.

31. Unbalanced bridge. When the Wheatstone bridge is not balanced, Ohm's law and Kirchhoff's laws give the following equations:

$$\begin{aligned} az &= C - B + E, & \alpha\xi &= A, & \xi + y - z &= 0, \\ by &= A - C, & \beta\eta &= B, & \eta + z - x &= 0, \\ cz &= B - A, & \gamma\zeta &= C, & \zeta + x - y &= 0. \end{aligned} \qquad (28)$$

Here E is the battery e.m.f., and A, B, C, denote the potentials of these points below that at O. These nine equations contain nine unknown quantities, viz., six currents and three potentials. Solving them as simultaneous equations any of the unknown quantities may be determined. For instance, the current in the galvanometer circuit is

$$\xi = \frac{E}{D}(b\beta - c\gamma), \qquad (29)$$

where the "determinant" D is given by

$$D = abc + bc(\beta+\gamma) + ca(\gamma+\alpha) + ab(\alpha+\beta) + (a+b+c)(\beta\gamma + \gamma\alpha + \alpha\beta).^*$$

32. Networks of conductors. In a general case (Fig. 2) as many Kirchhoff equations (Par. **29**) may be written as there are conductors; the unknown quantities may be the currents, the resistances or the voltages; also any combination of these, provided that the total number of unknown quantities is equal to the number of equations. The equations are conveniently solved by the method of determinants, found in most textbooks on algebra.

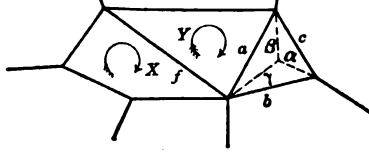


FIG. 4.—Method of simplifying networks.

33. Maxwell's solution. In some cases it is convenient to consider, instead of the actual currents, fictitious currents in each mesh (Maxwell, *ibid.*, Art. 282*b*). The actual current in each conductor is equal to the algebraic sum of the fictitious currents. For instance, in Fig. 4 the current in conductor f is the difference of the fictitious currents X and Y. The Kirchhoff equations are written for the fictitious currents.

* Maxwell, J. C. "A Treatise on Electricity and Magnetism," Vol. I, Art. 347.

For practical forms of the Wheatstone bridge and its application to the measurement of resistance see Sec. 3.

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An example of such a solution will be found in Del Mar's "Electric Power Conductors," p. 34.

34. Equivalent star and mesh (delta). The number of meshes, and consequently the number of equations, may be reduced, when some of the meshes are in the form of a triangle, like *abc* in Fig. 4. *For the three resistances forming the triangle may be substituted the three resistances* α, β, *and* γ, *which radiate from one point.*

The currents and the voltages in the rest of the network remain the same, provided that

$$\alpha = \frac{bc}{(a+b+c)}; \qquad \beta = \frac{ca}{(a+b+c)}; \qquad \gamma = \frac{ab}{(a+b+c)}. \tag{30}$$

The number of meshes is thus reduced by one. See Kennelly, A. E., *Electrical World and Engineer*, Vol. XXXIV (1899), p. 413. For a discussion of equivalent star- and delta-connected impedances for alternating currents see his "Application of Hyperbolic Functions to Electrical Engineering Problems," Appendix E.

35. In the practical case of distributing networks and feeders, the determination of the currents and voltages at the junction points is simplified by using the following **laws of superposition of currents and voltages.** (1) The true current at any point in the network is the algebraic sum of the currents which would flow if the consumers' currents were taken in succession instead of simultaneously. (2) The voltage drop to any point in the network is equal to the sum of the drops to the same point calculated under the assumption that the consumers' currents are taken in succession, and not simultaneously. Some simplification in the solution of the Kirchhoff equations is possibly due to the fact that the voltage drop along a conductor is usually small as compared to the voltage between it and the return conductor. For details of such calculations see Teichmuller, "Die Elektrischen Leitungen;" F. B. Crocker, "Network of Electrical Conductors," *El. World*, Vol. LIX (1912), pp. 799, 847, 901; Alex. Russell, "The Theory of Electric Cables and Networks," Chap. 4; Nowak, J., "A Machine for the Calculation of Supply Networks," *The Electrician*, Vol. LXVIII (1912), p. 748; Herzog and Feldmann, "The Distribution of Voltage and Current in Closed Conducting Networks," *Trans.* Inst. Elec. Congress, St. Louis, 1904, Vol. II, p. 699; also their book entitled "Die Berechnung Elektrischer Leitungsnetze," and Raiha und Seidener, "Starkstromtechnik," Sec. 8.

ELECTROMAGNETIC INDUCTION

36. Faraday's law of induction. When a magnetic flux Φ within a loop of wire varies with the time, an e.m.f. is induced in the loop, the instantaneous value e of the e.m.f. being proportional to the rate of change of flux;

$$e = -k\frac{\partial \Phi}{\partial t}, \tag{31}$$

where $\partial\Phi/\partial t$ is the rate of change of flux Φ with respect to the time t, and k is a constant which depends upon the units of voltage, flux, and time. When Φ is in maxwells, e in volts, and time in seconds, $k = 10^{-8}$. If the flux is expressed in webers, $k = 1$. The sign minus determines the relative directions of the flux and the e.m.f. Namely, when the circuit is closed, the induced e.m.f. tends to produce a current in the direction such as to oppose the change in flux. This latter statement follows from **Lenz's law**, which is stated by Maxwell* as follows: If a constant current flows in the primary circuit A, and if, by the motion of A, or of the secondary circuit B, a current is induced in B, the direction of this induced current will be such that, by its electromagnetic action on A, it tends to oppose the relative motion of the circuits. See the right-hand screw rule (Par. **56**) or Fleming's rule (Par. **57**). For practical purposes three particular cases of electromagnetic induction are considered below.

37. Stationary conductor and variable flux. This is the case when both the exciting m.m.f. which produces the flux, and the winding in which an e.m.f. is induced, are stationary, relatively to one another. The voltage is induced by a varying magnetic flux, the changes in the flux being produced by varying either the magnitude of the m.m.f. (stationary transformer) or

*Maxwell, J. C. "A Treatise on Electricity and Magnetism," Vol. II, Art. 542.

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the reluctance of the magnetic circuit (inductor-type alternator). If the flux is linked with N turns and varies harmonically with the time, at a frequency of f cycles per second, the **maximum induced e.m.f.** is

$$E_{max} = 2\pi f N \Phi_{max} 10^{-8} \text{ volts}, \tag{32}$$

where Φ_{max} is the maximum instantaneous value of the flux, in maxwells. The **effective value of the induced e.m.f.** is

$$E = 4.44 f N \Phi_{max} 10^{-8} \text{ volts}. \tag{33}$$

When the flux varies according to a law different from the sine law the effective voltage is

$$E = 4\chi f N \Phi_{max} 10^{-8}, \tag{34}$$

where χ is the form factor (Par. **207**).

The **average e.m.f. induced in one turn**, no matter what the law of variation of the flux with the time, is

$$E_{av} = \frac{\Phi_1 - \Phi_2}{t_2 - t_1}, \tag{35}$$

where the subscripts 1 and 2 refer to the initial and the final instants respectively.

38. Stationary flux and moving conductor. When the exciting m.m.f. which produces the flux, and the winding in which the e.m.f. is induced, move relatively to each other, as in a generator, so that the conductors cut across the lines of flux, the instantaneous induced e.m.f. in a conductor is

$$e = k\mathfrak{B}lv, \tag{36}$$

where $\mathfrak{B}$ is the flux density, l the length of the conductor, v the relative velocity between the flux and the conductor, and k a coefficient which depends upon the units selected. When e is in volts, $\mathfrak{B}$ in maxwells per square centimeter (gausses), l in centimeters and v in centimeters per second, $k = 10^{-8}$.

The three directions, $\mathfrak{B}$, l, and v, are supposed to be at right angles to each other; if not, their projections at right angles to each other are to be used in the preceding formula. For practical formulas giving the e.m.f. induced in direct-current and alternating-current machinery see Sec. 7 and Sec. 8.

39. Variable flux and moving conductor. When coils or conductors are moving through a pulsating magnetic field, as for instance in single-phase motors, the induced e.m.f. is due to a combined transformer and generator action (Par. **37** and **38**), and is equal at any instant to the sum of the e.m.f. induced by a constant flux in a moving coil and that induced by a pulsating flux in a stationary coil. Let the frequency of the pulsating field be f cycles per second; that of the rotating coil f' cycles per second. A pulsating field can be resolved into two revolving fields, one rotating clockwise, the other counter-clockwise. Therefore, the induced e.m.f. is a result of the superposition of two e.m.fs., one of the frequency $f+f'$, the other $f-f'$. In the particular case of $f = f'$ the e.m.f. induced in the rotating coil is of the frequency $2f$, the frequency $f-f'$ being equal to zero.

40. Force on a conductor carrying a current in a magnetic field. Let a conductor carry a current of i amp. and be placed in a magnetic field the density of which is $\mathfrak{B}$ maxwells per square centimeter ($\mathfrak{B}$ gausses). Then, if the length of the conductor is l cm., the force tending to move the conductor across the field is

$$F = 10.2 i \mathfrak{B} l 10^{-8} \quad \text{(kg.)} \tag{37}$$

It is presupposed in this formula that the direction of the axis of the conductor is at right angles to the direction of the field. If the directions of i and B form an angle α, the preceding expression must be multiplied by $\sin \alpha$.

The force F is perpendicular to both i and B, and its direction is determined by the right-hand screw rule (Par. **56**). Namely, the effect of the magnetic field produced by the conductor itself is to increase the original flux density ($\mathfrak{B}$) on one side of the conductor and to reduce it on the other side. The conductor tends to move away from the denser field.

41. The attraction or repulsion between two parallel straight conductors, carrying currents i_1 and i_2 (amp.) and placed in a non-magnetic medium, is calculated according to the formula

$$F = 2.04 i_1 i_2 \left(\frac{l}{b}\right) 10^{-8} \quad \text{(kg.)} \tag{38}$$

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where l/b is the ratio of the length of each conductor to the axial distance between the conductors. The force is an attraction or a repulsion according to whether the two currents are flowing respectively in the same or in the opposite directions.

Mechanical force exerted between magnetic flux and a current-carrying conductor is also present inside the conductor itself, and is called **pinch effect.** The force between the infinitesimal filaments of the current is an attraction, so that a current in a conductor tends to contract the conductor. This effect is of importance in some types of electric furnaces where it limits the current which can be carried by a molten conductor. The same stress also tends to elongate the conductor.

42. Interlinkage of electric and magnetic circuits. The most general relations between the electric and the magnetic quantities are expressed by **two laws of circuitation.*** Stripped of the vector-analysis terms in which these laws are usually expressed, they are as follows: Let H be the magnetic intensity or the m.m.f. gradient at a point in a medium of constant permeability, and let G be the electric intensity or the e.m.f. gradient at a point. The first law of circuitation states that the line integral of H along a closed curve is proportional to the volume of the total current (conduction current and displacement current) linked with this curve. The second law of circuitation states that the line integral of the electric intensity along a closed curve is proportional to the rate of change of the total magnetic flux linked with this curve. The coefficients of proportionality depend only upon the units used. The theory of propagation of electromagnetic waves is based upon these two laws. See for instance W. S. Franklin's "Electric Waves," Art. 57.

THE MAGNETIC CIRCUIT

43. The simple magnetic circuit. The simplest magnetic circuit is a uniformly wound torus ring (Fig. 5). The relation between the m.m.f. $\mathfrak{F}$ and the flux Φ is similar to Ohm's law (**19**), viz.,

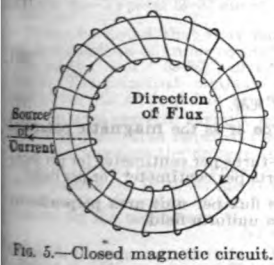


Fig. 5.—Closed magnetic circuit.

$$\mathfrak{F} = \mathfrak{R}\Phi \tag{39}$$

where $\mathfrak{R}$ is called the **reluctance** of the magnetic circuit. The same relation is sometimes written in the form

$$\Phi = \mathcal{P}\mathfrak{F} \tag{40}$$

where $\mathcal{P} = 1/\mathfrak{R}$ is called the **permeance** of the magnetic circuit. Reluctance is analogous to resistance and permeance is analogous to conductance of an electric circuit.

44. The m.m.f. does not depend alone on either the current in the winding or on the number of turns, but on the product of the two; therefore, **the natural unit for the m.m.f. is 1 amp-turn**, but in the practical system 1 amp-turn is 1.257 units of m.m.f. If the flux in the preceding equations is expressed in webers (one weber = 10^8 maxwells) the permeance is expressed in henrys (being of the nature of inductance). It has been proposed to call the corresponding unit of reluctance the yrneh, this being the word henry spelled backward, corresponding to ohm and mho. It has also been proposed to name the unit of permeance a perm, and the unit of reluctance a rel,† when the flux is in maxwells and the m.m.f. in ampere-turns, but no names have yet been generally accepted. In the C.G.S. electromagnetic system the unit of m.m.f. is the gilbert, equal to $10/4\pi = 0.7955$ amp-turn. Therefore the m.m.f. in gilberts, expressed as a function of ampere-turns, is

$$\mathfrak{F} = \frac{4\pi}{10} nI = 1.257nI \tag{41}$$

*Heaviside, O. "Electromagnetic Theory," Vol. I.
†Karapetoff, V. "The Magnetic Circuit;" McGraw-Hill Book Co. Inc., New York, 1912, Chap. I, and appendices.

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where nI is the product of the number of turns and the current in ampere
For further information about magnetic units see Sec. 1.

45. Permeability and reluctivity. The reluctance of a uniform ma
netic path (Fig. 5) is proportional to its length l and inversely proportion
to its cross-section A, or

$$\mathcal{R} = \nu \frac{l}{A} \tag{4}$$

and

$$\mathcal{P} = \mu \frac{A}{l}. \tag{4}$$

In these expressions ν is called the reluctivity and μ the permeability of t
material of the magnetic path. For air and all non-magnetic substance
ν and μ are assumed to be equal to unity per centimeter-cube, correspondi
to centimeter measure for l and A in (42) and (43), and the gilbert as t
unit of m.m.f. This is the conventional assumption in the C.G.S. ele
tromagnetic system and is the one generally employed. See also Par.
and **54**.

The method preferred by the author, and expounded in his "Magnet
Circuit" (see footnote reference in Par. **44**), is to take the ampere-turn
the unit of m.m.f. In such cases, with the maxwell as the unit of flux, t
permeability and the reluctivity of air, respectively, are

$$\left.\begin{aligned} \nu &= 0.7955 \text{ per cm.}^3 = 0.3132 \text{ per in.}^3 \\ \mu &= 1.257 \text{ per cm.}^3 = 3.193 \text{ per in.}^3 \end{aligned}\right\} \tag{4}$$

This method has the advantage of greater simplicity in calculations, but
not yet in general use (see Sec. 1; Giorgi system of units, Par. $3(d_2)$).

46. Magnetic field intensity $\mathfrak{IC}$ is defined as the m.m.f. per unit leng
of path. In any uniform field

$$\mathfrak{IC} = \frac{\mathfrak{F}}{l}. \tag{4}$$

In a non-uniform magnetic circuit

$$\mathfrak{IC} = \frac{\partial \mathfrak{F}}{\partial l}. \tag{4}$$

Inversely

$$\mathfrak{F} = \mathfrak{IC} l \text{ or } \mathfrak{F} = \int \mathfrak{IC} \partial l. \tag{4}$$

$\mathfrak{IC}$ is also known as the **magnetizing force** or as the **magnetic potenti
gradient.**

If $\mathfrak{F}$ is in ampere-turns, $\mathfrak{IC}$ is in ampere-turns per centimeter (or per inc
of length. If $\mathfrak{F}$ is in gilberts, $\mathfrak{IC}$ is in gilberts per centimeter (or per inch).

47. Flux density ($\mathfrak{B}$) is defined as the flux per unit area perpendicul
to the direction of the lines of force. In a uniform field

$$\mathfrak{B} = \frac{\Phi}{A}. \tag{4}$$

In a non-uniform field

$$\mathfrak{B} = \frac{\partial \Phi}{\partial A}. \tag{4}$$

Inversely

$$\Phi = \mathfrak{B} A, \text{ or } \Phi = \int \mathfrak{B} \partial A. \tag{5}$$

If the flux is measured in maxwells and areas in square centimete
flux density is expressed in maxwells per square centimeter; one maxw
per square centimeter is sometimes called a **gauss.** In this country
density is also expressed in maxwells, or in kilolines, per square inch.

It follows at once from (40), (43), (45) and (48) that

$$\mathfrak{B} = \mu \mathfrak{IC} \tag{5}$$

which is the familiar relationship between flux density, permeability and ma
netic field intensity.

48. Reluctances and permeances in series and in parallel. Relu
ances and permeances are added like resistances and conductances (Par.

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to 25), respectively. That is, *reluctances are to be added when in series, and permeances are to be added when in parallel.* If several permeances are given connected in series they are first converted into reluctances by taking the reciprocal of each. Similarly if reluctances are given in a parallel combination, they are first converted into permeances by taking the reciprocal of each.

49. Magnetization characteristic. The magnetic properties of a sample of steel or iron are represented by a **saturation** or **magnetization curve** (Fig. 6). Magnetic intensities $\mathfrak{IC}$ in ampere-turns per centimeter (or per inch) are plotted as abscissæ and the corresponding flux densities $\mathfrak{G}$ in kilolines per square centimeter (or per square inch) as ordinates. The curve is also known as the $\mathfrak{G}$–$\mathfrak{IC}$ curve.

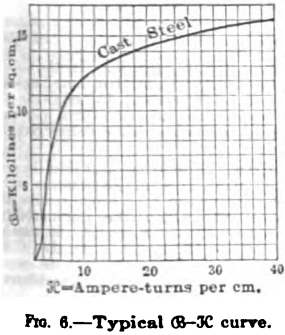


FIG. 6.—Typical $\mathfrak{G}$–$\mathfrak{IC}$ curve.

The practical use of a magnetization curve may be best illustrated by an example. Let it be required to find the number of exciting ampere-turns for magnetising a steel ring so as to produce in it a flux of 168,000 maxwells. Let the cross-section of the ring be 3 cm. by 4 cm., and the mean diameter 46 cm. Let the quality of the material be represented by the curve in Fig. 6. The flux density is $168{,}000/(3\times4) = 14{,}000$ maxwells per square centimeter or 14 kilogausses. For this flux density the corresponding abscissa from the curve is about 18 amp-turns per centimeter. The total required number of ampere-turns is $18\times\pi\times46 = 2{,}600$.

It may be noted that it is much more convenient to plot curves of $\mathfrak{G}$ using as abscissæ $\mathfrak{IC}$ in *ampere-turns* per unit length, rather than *gilberts* per unit length. For "$\mathfrak{G}$–$\mathfrak{IC}$" curves of various grades of steel and iron see Sec. 4. The principal methods for experimentally obtaining magnetization curves will be found in Sec. 3.

50. In a magnetic circuit consisting partly of iron and partly of air the ampere-turns required for establishing a certain flux are calculated by adding together the ampere-turns required for each part of the circuit. Let $\mathfrak{G}_i$ be the flux density (gausses) in the iron and l_i the length (centimeters) of the path in the iron, $\mathfrak{G}_a$ the flux density in the air and l_a the length of the air-gap in the direction of the lines of force. Then the total ampere-turns required for the circuit are

$$NI = \mathfrak{IC}_i l_i + \mathfrak{IC}_a l_a, \qquad (52)$$

where $\mathfrak{IC}_i$ (ampere-turns) is found from a saturation curve for the known value of $\mathfrak{G}_i$ (49) and $\mathfrak{IC}_a = 0.7955\mathfrak{G}_a$. If l_a is in inches, and $\mathfrak{G}_a$ in maxwells per square inch, $\mathfrak{IC}_a = 0.3132\mathfrak{G}_a$. The same method is applied if a magnetic circuit consists of more than two parts, as for instance the magnetic circuit of an electric generator or motor (Secs. 7 and 8). For numerous practical problems and solutions see the author's "Magnetic Circuit," pp. 27–31, and Chaps. V and VI.

51. Analysis of magnetization curve. Three parts are distinguished in a magnetization curve (Fig. 6), the lower or nearly straight part, the middle part called the **knee** of the curve and the upper part which is nearly a straight line. As the magnetic intensity $\mathfrak{IC}$ increases, the corresponding flux density $\mathfrak{G}$ increases more and more slowly, and the iron is said to approach **saturation**. The **percentage of saturation** and the **saturation factor** of a machine are defined in the Standardization Rules of the A. I. E. E. (Sec. 24).

52. Susceptibility and induced magnetization. A magnetic flux in iron or in another magnetic substance may be thought of as due to two causes: (1) the external applied m.m.f., and (2) the internal or molecular m.m.fs., induced by the applied m.m.f. Thus, we have

$$\mathfrak{I} = \varkappa\mathfrak{IC}, \qquad (53)$$

where $\mathfrak{IC}$ is the magnetic intensity due to the external m.m.f., and $\mathfrak{I}$ is the

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intensity of induced magnetization. The coefficient κ is called the **susceptibility** of the material. The total flux density in iron also consists of two parts, viz., that due to $\mathcal{H}$ and to $\mathfrak{J}$, or, in the C.G.S. system,

$$\mathfrak{B} = \mathcal{H} + 4\pi\mathfrak{J}. \tag{5}$$

Dividing both sides of this equation by $\mathcal{H}$, gives

$$\mu = 1 + 4\pi\kappa, \tag{5}$$

where μ is the permeability of the material (Par. **53**). Susceptibility is equal to zero for non-magnetic materials, is positive for paramagnetic and negative for diamagnetic substances. It is seldom used in practice.*

53. The permeability (μ) and the reluctivity (ν) of a material (Par. 45) are also defined as the ratios

$$\mu = \frac{\mathfrak{B}}{\mathcal{H}} \text{ and } \nu = \frac{\mathcal{H}}{\mathfrak{B}}. \tag{5}$$

Their values depend upon the units selected for $\mathfrak{B}$ and $\mathcal{H}$. In the C.G. electromagnetic system $\mathfrak{B}$ and $\mathcal{H}$ are numerically equal for non-magnetic materials, consequently $\mu = \nu = 1$. When $\mathfrak{B}$ is expressed in maxwells per square centimeter (or per square inch) and $\mathcal{H}$ in ampere-turns per unit length, μ and ν for air and other non-magnetic materials have values given in Par. **45**, Eq. 44.

54. Two different scales of permeability. For steel and iron the permeability $\mu = \mathfrak{B}/\mathcal{H}$ is frequently calculated from the magnetization curve (Par. **49**), and is usually plotted against $\mathfrak{B}$ as abscissæ (see curves in Sec. 4). One must be careful to distinguish between the **absolute permeability** and the **relative permeability.** The former is equal to $\mathfrak{B}/\mathcal{H}$, the latter the ratio of the permeability of a sample to that of the air. In the C.G. electromagnetic system both permeabilities are numerically the same because μ is assumed to be unity for the air; nevertheless they have different physical dimensions in any system of units.

55. Magnetic calculations. In practice, calculations of magnetic circuits with iron are usually arranged so as to avoid the use of permeability altogether, using a $\mathfrak{B}$–$\mathcal{H}$ curve directly (Par. **49** and **50**). In some special investigations it is convenient to use the values of permeability and also an empirical equation between μ and $\mathfrak{B}$. For small and medium flux densities this may be expressed as a parabolic curve, of the form

$$\mu = a - b(\mathfrak{B}_0 - \mathfrak{B})^2 10^{-6} \tag{5}$$

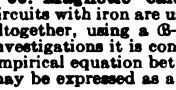


FIG. 7a.—Relation between directions of current and flux.

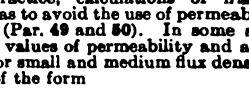


FIG. 7b.—Fleming's rules.

For numerical values of the coefficients see Sec. 4. It is also possible to represent the **relationship between $\mathfrak{B}$ and $\mathcal{H}$ for a magnetic material** empirically by a hyperbola (Fröhlich's formula)

$$\mathfrak{B} = \frac{\mathcal{H}}{\alpha + \beta\mathcal{H}}, \tag{5}$$

or also in the form

$$\text{reluctivity } \nu = \frac{\mathcal{H}}{\mathfrak{B}} = \alpha + \beta\mathcal{H} = \frac{1}{\mu}. \tag{5}$$

The coefficients α and β must be so determined as to satisfy the saturation curve of the particular material used.

56. The right-hand screw rule. The direction of the flux produced by a given current is determined as shown in Fig. 7*a* (see also Fig. 5). If the

* Maxwell, J. C. "A Treatise on Electricity and Magnetism," Vol. II, Arts. 426 to 428.

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current flows in the direction of rotation of a right-hand screw, the flux is in the direction of the progressive movement of the screw. If the current in a straight conductor is in the direction of the progressive motion of a right-hand screw, then the flux encircles this conductor in the direction in which the screw must be rotated in order to produce this motion. The dots in the figure indicate the direction of flux or current toward the reader; the crosses, that away from him.

57. The relative direction of flux, e.m.f. and motion in a generator may be determined with the right hand by placing the thumb, index- and middle fingers so as to form the three axes of a coordinate system and then pointing the index-finger in the direction of the flux (north to south) and the thumb in the direction of motion, the middle finger will give the direction of the generated e.m.f. (Fig. 7*b*). In the same way in a motor, using the left hand and pointing the index-finger in the direction of the flux and the middle finger in the direction of the current in the armature conductor, the thumb will indicate the direction of the force, and, therefore, the resulting motion. These two rules, indicated in Fig. 7*b*, are known as **Fleming's rules.**

58. Laplace's law. In a medium, the permeability of which is the same at all points, the magnetic field intensity produced at a point A by an element of a conductor ∂s (in cm.) through which a current of i amp. is flowing, is

$$\partial \mathfrak{H} = \frac{i\partial s \sin \alpha}{10r^2} \qquad \text{(gilberts per cm.)} \qquad (60)$$

where r is the distance between the element ∂s and the point A, in centimeters, and α is the angle between the directions of ∂s and r. The intensity $\partial \mathfrak{H}$ is perpendicular to the plane comprising ∂s and r, and its direction is determined by the right-hand screw rule given above. The field intensity produced at A by a closed circuit is obtained by integrating the above expression for $\partial \mathfrak{H}$ over the whole circuit.

59. The magnetic field due to an indefinite straight conductor carrying a current of i amp., consists of concentric circles which lie in planes perpendicular to the axis of the conductor and which have their centres on this axis. The **field intensity** at a distance of r cm. from the axis of the conductor is

$$\mathfrak{H} = \frac{2i}{10r} \qquad \text{(gilberts per cm.)}, \qquad (61)$$

its direction being determined by the right-hand screw rule (Par. 56).

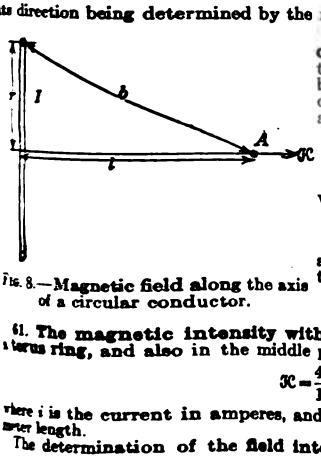


Fig. 8.—Magnetic field along the axis of a circular conductor.

60. Magnetic field due to a closed circular conductor. If the conductor carrying a current of I amp. is bent in the form of a ring of radius r cm. (Fig. 8), the magnetizing force at a point along the axis is

$$\mathfrak{H} = \frac{2\pi r^2 I}{10b^3} = \frac{0.2\pi r^2 I}{(\sqrt{r^2+l^2})^3} \qquad \text{(gilberts per cm.)}. \qquad (62)$$

When $l = 0$

$$\mathfrak{H} = \frac{0.2\pi I}{r} \qquad (63)$$

and when l is very great in comparison to r

$$\mathfrak{H} = \frac{0.2\pi r^2}{l^3} I. \qquad (64)$$

61. The magnetic intensity within a solenoid made in the form of a **torus ring,** and also in the middle part of a **long straight solenoid,** is

$$\mathfrak{H} = \frac{4\pi}{10} n_1 i \qquad \text{(gilberts per cm.)} \qquad (65)$$

where i is the current in amperes, and n_1 is the number of turns per centimeter length.

The determination of the field intensity produced by short coils is

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usually a complex matter, and the results are expressed by complicat formulæ. See references in Par. 74.

62. The stored magnetic energy in a single loop of non-magnetic wi when the dimensions of the wire are small compared to those of the loop (that the flux inside the wire is negligible), is

$$W = \tfrac{1}{2}i\Phi = \tfrac{1}{2}i^2\mathcal{P} = \frac{\Phi^2}{2\mathcal{P}} \qquad \text{(joules)} \qquad (6$$

where i is the current in amperes, Φ the flux linking with the loop, in webe and $\mathcal{P}$ the permeance of the magnetic path, in henrys.

63. Effect of leakage. When the flux linking with part of the turns o coil C is not negligible (see Fig. 9), the **total stored energy** may be expres in the following forms:

$$\left.\begin{aligned} W &= \tfrac{1}{2}i[n_c\Phi_c + \Sigma n_p\Delta\Phi_p], \\ W &= \tfrac{1}{2}i^2[n^2\mathcal{P}_c + \Sigma n_p{}^2\Delta\mathcal{P}_p]. \end{aligned}\right\} \qquad (6$$

The last expression is identical with

$$W = \tfrac{1}{2}Li^2 \qquad (6$$

where L is the inductance of the coil (Par. 67). The subscripts c in the fo going expressions refer to **complete linkages,** that is those which embra

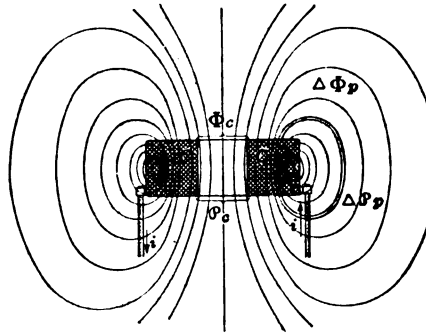


FIG. 9.—Magnetic field due to a coil.

all the turns of the coil, the subscripts p **to partial linkages.** See t author's "Magnetic Circuit," Art. 57.

64. The density of magnetic energy, or the magnetic energy stor per cubic centimeter of a magnetic field is

$$W' = \frac{\mu\mathfrak{H}^2}{8\pi} = \frac{\mathfrak{B}\mathfrak{H}}{8\pi} = \frac{\mathfrak{B}^2}{8\pi\mu} \qquad \text{(joules per cubic cm.).} \qquad (6$$

Here $\mathfrak{H}$ is the intensity in gilberts per centimeter, $\mathfrak{B}$ is the flux density webers per square centimeter and μ is the relative permeability; or if $\mathfrak{H}$ in ampere-turns per centimeter, then

$$W' = \tfrac{1}{2}\mu\mathfrak{H}^2 = \tfrac{1}{2}\mathfrak{B}\mathfrak{H} = \frac{\mathfrak{B}^2}{2\mu} \qquad \text{(joules per cubic cm.)} \qquad (6$$

where μ is the so-called absolute permeability (see Par. 54). To find total energy of a field the preceding expressions are multiplied by the elem of the volume ∂v and integrated within the desired limits of volume. an interesting comparison of practical possibilities as to the amount energy stored in the magnetic form per unit volume, compared with ot forms of energy, see Steinmetz, C. P., *General Electric Review*, 1913, 536.

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65. Magnetic tractive force.* The carrying weight of a lifting magnet is

$$F = \frac{A\mathfrak{G}^2}{24.64} \qquad \text{(kg.)} \tag{71}$$

where $\mathfrak{G}$ is the flux density in the air-gap, expressed in kilolines per square centimeter, and A is the total area of the contact between the armature and the core, in square centimeters. See also Sec. 5.

66. Magnetic force or torque. The mechanical force or the torque between two parts of a magnetic circuit may in some cases be conveniently calculated by making use of the principle of virtual displacements. An infinitesimal displacement between the two parts is assumed, and the assumption is made that the work necessary for this displacement is equal to the change in the stored magnetic energy, plus the electrical energy added during the change from the source of the exciting current. For details see the author's "Magnetic Circuit," Art. 71.

INDUCTANCE

67. The electromagnetic inductance, or the coefficient of self-induction L, is defined from any of the following three fundamental equations:

$$e = -L\frac{di}{dt}; \tag{72}$$

$$W = \tfrac{1}{2}i^2L; \tag{73}$$

$$L = n_c{}^2\mathcal{P}_c + \int_0^n n_p{}^2 d\mathcal{P}_p. \tag{74}$$

These expressions are true only when the permeability of the medium is constant. The first equation expresses the fact that the self-induced voltage is proportional to the rate of change of the current in the circuit, and L is the coefficient of proportionality. According to the second equation, the magnetic energy stored in a circuit is proportional to the square of the current (Par. 63), and L is the coefficient of proportionality. In the third formula L is expressed through the permeances $\mathcal{P}$ of the magnetic paths linking with the circuit (Fig. 9), and the number of turns with which these paths are linked. The subscripts c and p refer to complete and partial linkages respectively (Par. 63). For practical purposes both inductance and permeance are expressed in henrys (Par. 44 and Sec. 1). The first expression is convenient for measurements of inductance, the third one for calculations in those cases where the shape of the magnetic paths is known or can be estimated.

68. Closed magnetic circuit. For a **torus ring** (Fig. 5) **uniformly wound with one layer of thin wire** the partial linkages may be neglected, so that $n_p = 0$, and $\mathcal{P}_c = \mu A/l$, where for non-magnetic materials $\mu = 1.000$; A is the cross-section of the flux within the ring, and l is the average length of the flux. Consequently

$$L = \frac{1.257 n_c{}^2 A}{l}\mu_r 10^{-8} = 1.257 n_1{}^2 l A\, 10^{-8} \qquad \text{(henrys)} \tag{75}$$

In this expression n_c is the total number of turns, and $n_1 = n_c/l$ is the number of turns per centimeter length of the magnetic path; l and A are in square centimeters; μ_r is the relative permeability of the core with respect to the air (Par. 54).

69. For a torus ring of rectangular cross-section wound with several layers of wire the inductance is

$$L = 0.4\frac{n^2}{D}[bh + \tfrac{2}{3}t(b + h + t)]10^{-8} \qquad \text{(henrys)} \tag{76}$$

In this expression b and h are the dimensions of the non-magnetic core on which the wire is wound, D is the mean diameter of the ring, n is the total number of turns, and t the thickness of the winding (all in centimeters). If the core is magnetic, the product bh must be multiplied by the relative

*Maxwell, J. C. "Treatise on Electricity and Magnetism;" Cambridge University Press; Vol. II, Art. 643.

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permeability of the steel. If the magnetic core occupies only a part α the cross-section bh, use the expression $bh[\alpha\mu_r+(1-\alpha)]$, in place of bh.

70. For other calculations of inductance using formula (68) see t author's "Magnetic Circuit," Chaps. X to XII.

71. Thin solenoids. For a straight coil uniformly wound with n_1 tu per centimeter length, provided that the length of the coil is large co pared to its transverse dimensions, and that the winding consists of one la of comparatively thin wire, **the inductance is**

$$L = 1.257 n_1^2 A 10^{-8} \quad \text{(henrys)} \quad (\text{(illegible)}$$

the notation being the same as in Par. **68.**

72. The inductance of a long straight coil wound with several lay of wire, and with an iron core of radius a inside,

$$L = 4\pi n_1^2 l d^2 r^2 \left[1 + (\mu_r - 1)\frac{a^2}{r^2}\frac{d}{r} + \frac{d^2}{3r^2}\right] 10^{-8} \quad \text{(henrys)} \quad (\text{(illegible)}$$

where r is the inside radius of the winding, and d its radial thickness; n_1 is the number of turns per centimeter length, and all the dimensions are in centimeters. If there is no iron core, put $a = 0$.

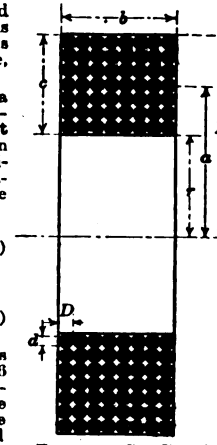


FIG. 10.—See Par. 73.

73. Prof. Morgan Brooks has derived a universal semi-empirical formula for the **inductance of short and long coils without iron cores.** His formula is given below in two forms, one (79) for dimensions in centimeters, the other (80) for dimensions in English units. Both give results in henrys. The notation is explained in Fig. 10.

$$L = \frac{Cm^2}{b+c+R} \times \frac{F'F''}{10^9} \quad \text{(henrys)} \quad (79)$$

$$L = \frac{0.366\left(\frac{Ft}{1000}\right)^2}{b+c+R} \times F'F'' \quad \text{(henrys)} \quad (80)$$

In Eq. (80) the conductor length is in thousands of feet, and the coil dimensions in inches; 0.366 is the conversion factor. F' and F'' are empirical coil-shape factors dependent upon the relative, and independent of the absolute dimensions of the winding. Values of F' and F'' are as follows:

$$F' = \frac{10b+12c+2R}{10b+10c+1.4R}; \quad F'' = 0.5 \log_{10}\left(100 + \frac{14R}{2b+3c}\right). \quad (\text{(illegible)}$$

Cm indicates the length of the conductor in centimeters;
Ft indicates the length of the conductor in feet, and $Ft/1000$ = thousand feet;
N is the total number of turns in the winding, whence

$Cm = 2\pi aN$, when a is in centimeters, and

$\frac{Ft}{1000} = \frac{2\pi aN}{12000}$ when a is in inches.

Numerous tables, curves, and charts which simplify the use of this form for practical design will be found in the Bulletin No. 53 of the Univer of Illinois, by Morgan Brooks and H. M. Turner, entitled "Inductanc Coils." For another empirical formula see Doggett, L. A., "The Induct of Air-cored Solenoids," *Elec. World*, Vol. LXIII (1914), p. 259.

74. Bureau of Standards, formulas for inductance. For a thoro analysis and comparison of various formulas for the inductance of coils reader is referred to the following excellent series of articles published in Bulletin of the Bureau of Standards:

"Formulæ and Tables for the Calculation of Mutual and Self-inductan (Revised), E. B. Rosa and L. Cohen, Vol. VIII, p. 1; 1912; "Calculatio

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the Self-inductance of Single-layer Coils," Edward B. Rosa. Vol. II, p. 161; 1906; "The Self-inductance of a Coil of any Length Wound with any Number of Layers of Wire," Edward B. Rosa. Vol. IV, p. 369; 1907; "Self-Inductance of a Solenoid of any Number of Layers," Louis Cohen. Vol. IV, p. 383; 1907; "Construction and Calculation of Absolute Standards of Inductance," J. G. Coffin. Vol. II, p. 37; 1906.

"Revision of the Formulas of Weinstein and Stefan for Mutual Inductance of Coaxial Coils," Edward B. Rosa. Vol. II, p. 331; 1906; "The Mutual Inductance of Two Circular Coaxial Coils of Rectangular Section," Edward B. Rosa and Louis Cohen. Vol. II, p. 359; 1906. See also E. Orlich, "Kapasität und Induktivität" (Vieweg), p. 74. and Louis Cohen, "Formulæ and Tables for the Calculation of Alternating-current Problems," Chap. 2.

75. The inductance of a concentric cable is (Fig. 11)

$$L = 0.4605 \log_{10}\left(\frac{b}{a}\right) + 0.05 + L' \quad \text{(millihenrys per km.)} \qquad (84)$$

where

$$L' = \frac{t}{15b}\left[1 - \frac{1}{10}\left(\frac{t}{b}\right)^2 + \frac{3}{40}\left(\frac{t}{b}\right)^3 + \ldots\right] \qquad (85)$$

The foregoing expression for L is true at **low frequencies** only. At high frequencies an unequal distribution of currents reduces the partial linkages so that in general

$$L = 0.4605 \log_{10}\left(\frac{b}{a}\right) + k(0.05 + L'). \qquad (86)$$

Here $k = 1$ at usual industrial frequencies, and gradually approaches zero as the frequency increases to infinity.

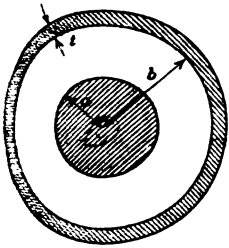


FIG. 11.—Cross-section of concentric cable.

76. N-conductor cables. For the **field distribution** in and the **inductance of non-concentric cables** see Alex. Russell, "Alternating currents," Vol. I; for the **inductance of armored cables** see J. B. Whitehead, "The Resistance and Reactance of Armored Cables," Trans. A. I. E. E., Vol. XXVIII (1909), p. 737.

77. The inductance of a single-phase transmission line is given by

$$L = 0.4605 \log_{10}\frac{b}{a} + 0.05, \text{ in millihenrys per kilometer of one conductor,} \qquad (87)$$

where a is the radius of the conductors, and b is the distance between their centres. To find the inductance per mile multiply by 1.609. To find the inductance per thousand feet divide by 3.281. For tables of reactance (Par. 184) at usual frequencies and spacings see Sec. 11.

78. For iron conductors use $0.05\mu_r$ instead of 0.05 in the above formula, where μ_r is the relative permeability of the iron with respect to the air. The value of μ_r varies with the current, and also depends upon the quality of the iron. For good telegraph wire μ_r is equal approximately to 150.

79. For stranded conductors the actual radius is too large to be used in the formula for inductance. For all practical purposes, the equivalent radius of a stranded conductor may be assumed the same as that of a solid round conductor of the same sectional area. For an accurate calculation of the inductance of stranded conductors see Dwight, H. B., *Electrical World*, 1913, Vol. LXI, p. 828.

80. The inductance of a three-phase line with symmetrical spacing, per wire, is the same as the inductance of a single-phase line per wire, with the same size of wire and the same spacing. It is expressed by the formula (87) in Par. 77. This formula holds true for balanced as well as unbalanced loads, for balanced and unbalanced line voltages, for a three-wire two-phase system, three-wire single-phase system, monocyclic system, etc.

81. For a semi-symmetrical spacing of a three-phase line, that is when two spacings are equal, and the third is different, formula (87) in

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Par. 77 holds true only for the conductor situated symmetrically with respec to the other two. The inductance of the other two wires cannot be ca culated in a simple manner. For practical purposes it is sufficient to tak the inductance of all three wires as equal to that of a line symmetricall spaced, the equivalent spacing being equal to the geometric mean of the thre actual spacings, or

$$b_{eq} = \sqrt[3]{b_1 b_2 b_3}. \qquad (88$$

82. For the equivalent resistance and reactance of a three-phas line with unequal spacings of wires see the writer's "Magnetic Circuit" Art. 63. In this case the e.m.f. induced in a conductor by the varying mag netic fluxes consists of two components, one being in quadrature, the oth in phase with the current in the conductor. The first component correspond to the inductance of the conductor, the other represents transfer of pow from one phase to the others. In general, these components are differe for the three conductors, and in order to equalise them for the whole lin conductors are transposed after a certain number of spans. This **transpos tion of conductors** is used on power lines (Sec. 11) as well as on telegrap and telephone lines (Sec. 21) to reduce the unbalancing effect of mutual i duction. See also Par. **87** below. The inductance of two or more parall cylinders of any cross-section can be expressed through the so-called ge metric mean distance introduced by Maxwell.* For details also see Orlic "Kapazität und Induktivität," pp. 63–74.

83. Mutual inductance. When two independent electric circuit (1) and (2), are in proximity to each other, their electromagnetic energy ma be said to consist of three parts: the part due to the linkages of the flux pr duced by the circuit (1) with the current in (1); that due to the flux produc by the circuit (2) with the current in (2); and that due to the current in ea circuit linking with the flux produced by the other circuit. Employing t notation in Par. **67**, the total energy of the system is expressed by

$$W = \tfrac{1}{2} i_1^2 L_1 + \tfrac{1}{2} i_2^2 L_2 + i_1 i_2 L_m \qquad \text{(joules)} \qquad (8$$

where L_1 and L_2 are the coefficients of self-induction of the two circuits, a L_m is called the **coefficient of mutual inductance** of the two circuit All three coefficients are measured in henrys.

84. The coefficient of mutual inductance is also defined from t relations:

$$e_1 = -L_m \frac{di_2}{dt}, \text{ or } e_2 = -L_m \frac{di_1}{dt}, \qquad (9$$

that is, L_m determines the voltage e_1 induced in the circuit (1) when the curre i_2 in circuit (2) varies with the time, and *vice versa*.

85. The coefficient of mutual inductance of two long coaxi single-layer coils of the same length l and cross-section A, is

$$L_m = 1.257 n_1 n_2 l A 10^{-8}, \text{ (henrys)}, \qquad (9$$

where n_1 and n_2 are the numbers of turns per centimeter length of the t coils respectively; l and A are measured in centimeters.

86. For two long coaxial coils wound in several layers the coefficie of mutual inductance is

$$L_m = 4\pi n_1^2 n_2^2 l d_1 d_2 r_1^2 \left(1 + \frac{d_1}{r_1} + \frac{d_1^2}{3 r_1^2}\right) \qquad \text{(henrys)} \qquad (9$$

and if an iron core is present

$$L_m = 4\pi n_1^2 n_2^2 l d_1 d_2 r_1^2 \left[1 + (\mu_r - 1)a^2 + \frac{d_1}{r_1} + \frac{d_1^2}{3 r_1^2}\right] \quad \text{(henrys)} \quad (9$$

For explanation of notation see Par. **72** above. See also the referenc in Par. **74**.

87. The coefficient of mutual inductance of two parallel lin circuits (Fig. 11*a*) is given by

$$L_m = 0.4605 \log_{10}\left(\frac{a_1 b_2}{b_1 a_2}\right) \quad \text{(millihenrys per km.)} \quad (9$$

where a_1 and b_1 are the distances from one of the wires of circuit 1 to t

* Maxwell, J. C. "Treatise on Electricity and Magnetism," Vol. II, p. 32

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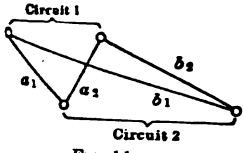


FIG. 11*a*.

conductors of the other circuit, and a_2 and b_2 are the corresponding distances of the other wire of circuit 1 from the conductors of the other circuit. For **interference between transmission and telephone lines** due to mutual inductance see Sec. 21. Transposition of telephone lines is also explained in Sec. 21.

88. Actual measurement must be employed in most cases to determine the coefficient of **mutual inductance.** See Sec. 3.

HYSTERESIS AND EDDY CURRENTS

89. The hysteresis loop. When a sample of iron or steel is subjected to an alternating magnetisation, the relation between $\mathfrak{G}$ and $\mathfrak{IC}$ (Par. 49) is different for increasing and decreasing values of the magnetic intensity (Fig. 12). This phenomenon may be thought of as due to some kind of friction between the molecules of the magnetic material. Each time the current wave completes a cycle, the magnetic flux wave must also complete a cycle and each molecular magnet be turned through one revolution. This loss appears as heat. The figure *AefBcdA* in Fig. 12 is called the hysteresis loop.

90. Retentivity. If the coil shown in Fig. 5 be excited with alternating current, the ampere-turns and consequently the m.m.f. will, at any instant, be proportional to the instantaneous value of the exciting current. Plotting a $\mathfrak{G}$-$\mathfrak{F}$ or a $\phi - \mathfrak{F}$ curve (Fig. 12) for one cycle, the closed loop, *cdAefB*, is obtained. The first time the iron is magnetized the **virgin** or **neutral curve**, *0A*, will be produced; but it cannot be produced in the reverse direction, *A0*, because when the m.m.f. drops to zero there will always be some magnetism (*+Oe* or *−Oc*) left. This is called **residual magnetism** and in order to reduce this to zero, an m.m.f. (*−Of* or *+Od*) of opposite polarity must be applied. This m.m.f. is called the **coercive force.**

91. Wave distortion. In Fig. 12 the instantaneous values of the exciting current *I* (which is directly proportional to the m.m.f.), and the corresponding values of the flux ϕ and voltage *E* (or *e*) are plotted against time as abscissæ, side by side with the hysteresis loop. (*a*) If the *voltage* applied to the coil is *sinusoidal* (*E*, to the left), the current wave will be distorted and displaced from the corresponding sinusoidal flux wave. The latter wave is in quadrature with the voltage wave. (*b*) If the *current* through the coil is *sinusoidal* (*I*, to the right), the flux is distorted into a flat-top wave, and the induced voltage wave *e* is peaked.

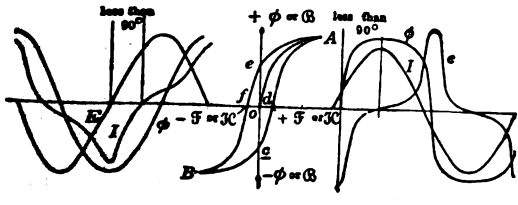


FIG. 12.—Periodic waves of current, flux and e.m.f.; hysteresis loop.

92. Components of exciting current. The alternating current which flows in the exciting coil (Fig. 12) may be considered to consist of two components, one exciting magnetism in the iron, and the other supplying the hysteresis loss. For practical purposes both components may be replaced by equivalent sine-waves, and finally by vectors (Fig. 13). We have

$I_r = I \cos\theta$ = power component of the current;
$P_h = IE \cos\theta = I_r E$ = hysteresis loss in watts,
$I_m = I \sin\theta$ = magnetising current,

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wherein I is the total exciting current and θ the angle of time-phase displacement.

The **energy lost per cycle** can be represented by the area, $AfBd$, of the loop; see Par. **94** below.

93. Hysteretic angle. Without hysteresis, the current I would be in phase quadrature with E. For this reason the angle $\alpha = 90 - \theta$ is called **the angle of hysteretic advance of phase.**

$$\text{Sin } \alpha = \frac{I_r}{I} = \frac{I_r E}{IE} = \frac{\text{watts loss}}{\text{apparent watts}}. \qquad (95)$$

In practice, the measured loss usually includes eddy currents (Par. **98**) so that the name "hysteretic" is somewhat of a misnomer.

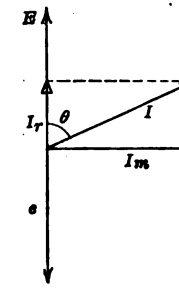


FIG. 13.—Componen of exciting current; hy teretic angle.

94. The energy lost per hysteresis cycle (Fig. 12) is proportional to the area of the loop, o$_r$

$$\text{Energy} = cV \sum_{-\mathfrak{B}}^{+\mathfrak{B}} \mathfrak{H}\Delta\mathfrak{B} \qquad \text{(Joules)} \qquad (96)$$

wherein V is the volume of the iron, $\mathfrak{B}$ and $\mathfrak{H}$ being the coordinates of the loop instead of Φ and $\mathfrak{F}$ as shown in Fig. 12; and c a constant depending upon the scale used. For details see the author's "Magnetic Circuit Art. 16.

95. Steinmetz's formula. According to exhaustive experiments Dr. C. P. Steinmetz, the heat energy released per cycle per cubic centimet of iron is approximately

$$W = \eta B^{1.6}_{max} \qquad \text{(ergs)} \qquad (9$$

The exponent of $\mathfrak{B}$ varies between 1.4 and 1.8 but is generally taken 1.6. Values of η are given in Sec. 4 (see index).

96. Power loss per unit weight. The most convenient way to expr the **hysteresis loss** is

$$P_h = k_h \frac{f}{100}\left(\frac{\mathfrak{B}_{max}}{1000}\right)^{1.6} \qquad \text{(watts per unit weight)} \qquad (9$$

wherein f is the frequency in cycles per second; $\mathfrak{B}$ the maximum flux dens in lines or maxwells per square centimeter, and k_h a constant; see Sec. 4.

97. Two-term formula. Another empirical formula for the **hystere loss** is

$$P_h = f(\eta' B + \eta'' B^2) \qquad \text{(watts per unit weight)} \qquad (9$$



FIG. 14. Eddy currents.

where η' and η'' are empirical coefficients. This form is more accurate at medium and high flux densities th the preceding one.

98. Eddy-current losses are I^2R losses (Par. **27**) d to secondary currents (Foucault currents) established those parts of the circuit which are interlinked with alt nating or pulsating flux. Referring to Fig. 14, a b shaped conductor is just entering a non-uniform fie The advancing side, A, is cutting more lines than t trailing side, B, so that there is a difference in potent between these two sides and electricity will flow as sho by the arrows. According to the formula e^2g, eq. (2 the loss is proportional to the cube of the thickness t, cause both e and g are proportional to t. Hence loss per unit volume of conductor is proportional to square of the thickness. It is assumed that the length much greater than the width, and that the third dim sion is constant.

Referring to Fig. 15, which shows a cross-section of a transformer core, primary current, I, produces the alternating flux, Φ, which by its char generates an e.m.f., e, in the core; this e.m.f. then sets up the seconds

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current, i. Now, if the core be divided into two (*b*), four (*c*), or n parts, the e.m.f. in each circuit will be $e/2$, $e/4$, e/n and the conductance $g/2$, $g/4$, g/n respectively. Thus, the loss per lamination will be $(1/n^2)$-th part and the total loss $(1/n^2)$-th part of the loss in the solid core.

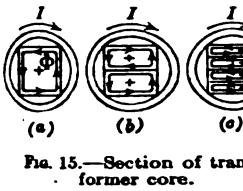


FIG. 15.—Section of transformer core.

99. Effect of lamination. From the two examples given above it is seen that the eddy currents can be greatly reduced by laminating the circuit, *i.e.*, by making it up of thin sheets each insulated from the others. The same purpose is accomplished by using stranded conductors or bundles of wires. **The eddy-current loss in a laminated iron core is**

$$P_e = k_e\left(\frac{tf\mathfrak{B}_{max}}{1000}\right)^2 \quad \text{(watts per unit weight)} \quad (100)$$

wherein t is the thickness of the laminations in mils; f the frequency in cycles per second, and k_e a factor including the specific weight and resistivity of the material.

A formula for the **loss in conductors of circular section**, such as wire, is

$$P_e = \frac{(\pi f \mathfrak{B}_{max})^2}{4\rho\ 10^{16}} \quad \text{(watts per cu. cm.)} \quad (101)$$

wherein r is the radius of the wire in centimeters; f the frequency in cycles per second; $\mathfrak{B}_{max}$ is the maximum flux density in lines per square centimeter and ρ the specific resistance in ohms per centimeter cube.

A formula for the **loss in sheets** is

$$P_e = \frac{(\pi t f \mathfrak{B}_{max})^2}{6\rho\ 10^{16}} \quad \text{(watts per cu. cm.)} \quad (102)$$

wherein t is the thickness in centimeters; f the frequency in cycles per second; B_{max} is the maximum flux density in lines per square centimeter, and ρ the specific resistance.

The specific resistance of various materials is given in Sec. 4 (see index).

100. Real or ohmic resistance is the resistance offered by the conductor to the passage of electricity. Although the specific resistance is the same for either alternating or continuous current, the total resistance of a wire is greater for alternating than for continuous current. This is due to the fact that in a conductor which is continuously cut by flux, there are generated e.m.fs.; these e.m.fs. are greater at the centre than at the circumference so that the potential difference tends to establish currents which oppose the main current at the centre and assist it at the circumference. The result is, that the main current is forced to the outside thus reducing the effective area of the conductor. This phenomenon is called skin effect (Par. **101**).

101. A theoretical formula for the calculation of skin effect in a solid conductor of circular cross-section is*

$$r = R\left[1 + \frac{1}{12}\left(\frac{2\pi f l\mu}{R10^9}\right)^2 - \frac{1}{180}\left(\frac{2\pi f l\mu}{R10^9}\right)^4 + \text{etc.}\right] \quad \text{(ohms)}, \quad (103)$$

wherein r is the resistance offered to an alternating current; R that offered to a continuous current; f the frequency in cycles per second, μ the relative permeability of the conductor and l the length of the conductor in centimeters.

It will be noted that $1/R$ is proportional to the area of cross-section of the conductor; therefore, the skin effect depends upon the area of cross-section of the conductor and the frequency of the current. These should be kept as small as possible, although skin effect seldom cuts any great figure where moderate sized conductors are used to carry current at ordinary frequencies. It is in iron or other magnetic materials, where skin effect becomes really important. It must be considered in rail returns for alternating-current systems. Skin effect tables are given in Sec. 4 (see index). For a detailed

* Maxwell, J. C. "A Treatise on Electricity and Magnetism," Vol. II, Art. 690; footnote by J. J. Thomson.

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treatment of resistance to alternating currents and eddy current losses in metallic conductors see Louis Cohen, "Formulæ and Tables for the Calculation of Alternating-current Problems," Chap. I. Numerous tables and formulæ will be found there, relating to the resistance to alternating currents and eddy current losses in solid, hollow and concentric cylindrical conductors, flat conductors, coils and conductors in slots of laminated iron armatures.

102. Effective resistance and reactance. When an alternating-current circuit has appreciable hysteresis, eddy currents and skin effect, it can be replaced by an equivalent circuit, without these losses, by using **equivalent resistances** and **equivalent reactances** (Par. **154**) in place of the real ones. These equivalent or effective quantities are so chosen that the energy relations are the same in the equivalent circuit as in the actual one. In a series circuit let the true power lost in ohmic resistance, hysteresis, and eddy currents be P, and the reactive (wattless) volt-amperes P'. Then the effective resistance and reactance are determined from the relations

$$i^2 r_{eff} = P; \quad i^2 x_{eff} = P'. \tag{104}$$

In a parallel circuit, with a given voltage, the equivalent conductance and susceptance (Par. **169**) are calculated from the relations

$$e^2 g_{eff} = P; \quad e^2 b_{eff} = P'. \tag{105}$$

Such equivalent electric quantities which replace the core loss are used in the analytical theory of transformers and induction motors.

103. Core loss. In practical calculations of electrical machinery the total core loss is of interest rather than the hyteresis and the eddy currents separately. For such computations empirical curves are used, obtained from tests on various grades of steel and iron (see Sec. 4).

104. The separation of hysteresis from eddy currents. For a given sample of laminations, the total core loss P, at a constant flux density and at variable frequency f, can be represented in the form

$$P = af + bf^2 \tag{106}$$

where af represents the hysteresis loss and bf^2 the eddy or Foucault-current loss, a and b being two constants. If we write this equation for two known frequencies, two simultaneous equations are obtained from which a and b are determined.

105. Determination of constants. It is convenient to divide the foregoing equation by f, because in the form

$$\frac{P}{f} = a + bf \tag{107}$$

it represents the equation of a straight line between (P/f) and f. Having plotted the known values of (P/f) against f as abscissæ, the most probable straight line is drawn through the points thus obtained. The intersection of this line with the axis of ordinates gives a; b is calculated from the preceding equation. Knowing a and b, the separate losses are calculated at any desired frequency from the expressions af and bf^2 respectively.

THE DIELECTRIC CIRCUIT

106. Dielectric flux. When a source of continuous voltage E (Fig. 16) is applied at the terminals of a **condenser** AB, a quantity of electricity Q flows through the connecting wires and the same quantity of electricity may be said to be displaced through the dielectric between the condenser terminals, because electricity behaves like an incompressible fluid. This displaced electricity in a dielectric is called the dielectric flux and is measured in the same units as a quantity of electricity in a conducting circuit; that is, in coulombs or in microcoulombs.

107. The dielectric flux density and the potential gradient. The flux density D or the dielectric flux per unit area is $D = Q/A$ when the flux distribution is uniform, or $D = \partial Q/\partial A$ when the flux distribution is non-uniform. In these expressions Q is the dielectric flux and A is the area perpendicular to the electrostatic lines of force. Flux density is measured in microcoulombs per square centimeter or per square inch.

The voltage E applied at the terminals of the condenser acts upon the whole thickness l of the dielectric, and the **dielectric stress** G is characterized as the voltage per unit thickness (unit length) of the dielectric in the direction

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of the lines of force. Thus, in a uniform field, $G = E/l$, and in a non-uniform field, $G = \partial E/\partial l$. The dielectric stress G is also called the **voltage gradient** or the **electric force.** It is measured in volts per inch, kilovolts per mm., or in other such convenient units.

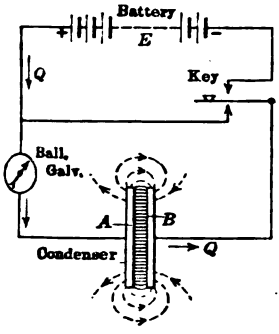


FIG. 16.—Circuit containing a condenser.

In a homogeneous dielectric, the flux density D at any point is proportional to the voltage gradient at that point, and the ratio of the two characterizes the material; or, $D = \kappa G$, where κ is called the **absolute permittivity** of the dielectric. See Par. **113** and **134.**

108. Electrostatic capacity (or permittance). The displacement Q of electricity through a dielectric is proportional to the voltage E applied between the terminals (Fig. 16) as long as the safe limit of insulation is not exceeded; or

$$Q = CE \tag{108}$$

where the coefficient of proportionality C is called the electrostatic capacity or permittance of the condenser. When E is in volts and Q in coulombs, C is in farads. If Q is in microcoulombs, C is in microfarads.

When the applied voltage is variable, the preceding equation is written in the form

$$i_c = \frac{\partial Q}{\partial t} = C\,\frac{\partial E}{\partial t}, \tag{109}$$

where Q and E are differentiated with respect to time t, and i_c is called the **charging** or **displacement current.** Either this equation or the relation $Q = CE$ may be considered as the fundamental one defining capacity C.

109. Elastance. The same proportionality between the applied voltage and the displacement of electricity is sometimes written in the form

$$E = SQ, \tag{110}$$

where $S = 1/C$ is called the **elastance** of the condenser. When E is in volts and Q in coulombs, S is measured in units which the author has termed "darafs" (farad spelled backward). When Q is in microcoulombs, S is in "megadarafs."

110. Condensers in series and in parallel. When condensers are connected in parallel, the equivalent capacity is equal to the sum of all the capacities of the component condensers, or

$$C_{eq} = \Sigma C. \tag{111}$$

When two or more condensers are connected in series, the equivalent capacity is determined from the relation

$$\frac{1}{C_{eq}} = \Sigma \frac{1}{C}. \tag{112}$$

Analogously, for a **series connection of elastances** (Par. **109**)

$$S_{eq} = \Sigma S; \tag{113}$$

and for **parallel connection of elastances**

$$\frac{1}{S_{eq}} = \Sigma \frac{1}{S}. \tag{114}$$

111. For example, let two permittances $C_1 = 0.2$ mf. and $C_2 = 0.3$ mf. be connected in parallel with each other, and in series with a third condenser for which $C_3 = 0.4$ mf. To find the total capacity of the combination we note that the combined capacity of the two condensers in parallel is $C_1 + C_2 = 0.5$ mf., or the elastance of the combination is two megadarafs. The elastance of the third condenser is $1/C_3 = 2.5$ megadarafs, so that the total elastance of the combination is $2 + 2.5 = 4.5$ megadarafs. Consequently the equivalent capacity is $1/4.5 = 0.222$ mf. This example shows the convenience of using elastances when condensers are connected in series.

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112. The specific inductive capacity of a dielectric (k) is the ratio between the capacity of a condenser made entirely of this dielectric and of an identical condenser using air for dielectric. It is also termed the dielectric constant. Another name for specific inductive capacity is **relative permittivity.** For numerical values for various dielectrics see Sec. 5.

113. Capacity (permittance) between parallel plates. When a condenser consists of two parallel plates the distance between which is small compared to the dimensions of the plates, the lines of electrostatic displacement are nearly straight lines normal to the adjacent surfaces of the plates. The capacity of such a condenser is

$$C = \left(\frac{k}{4\pi}\right)\frac{A}{l} \qquad \text{(abstatfarads)} \qquad (115)$$

where A is the area of one of the plates in sq. cm., l the normal distance between them, in cm. and $k/4\pi$ the **permittivity** of the dielectric; k is the dielectric constant, which for air is unity. If C is to be in microfarads, then in the preceding formula in place of $k/4\pi$ use

$$\frac{k}{4\pi}\left(\frac{1}{v^2}\right) = 0.08842 \times k \times 10^{-6} \quad \text{(mf. per centimeter-cube)} \qquad (116)$$

where v is the velocity of light, or the factor required to change from electrostatic to electromagnetic units.

If instead of taking $k/4\pi$ as the permittivity, a term k_a called the absolute permittivity is introduced, then

$$C = k_a \frac{A}{l} \qquad \text{(microfarads)} \qquad (117)$$

And for air, instead of unity (the relative permittivity), the absolute permittivity is

$$\kappa_a = 0.08842 \times 10^{-6} \qquad \text{(mf. per centimeter-cube)} \qquad (118)$$

and for any other substance the absolute permittivity would be $0.08842 \times 10^{-6}k$, where k is the specific inductive capacity or the relative permittivity of the dielectric; see Par. **112.** See also the author's "Electric Circuit," Article 51, for further elaboration of this theory of absolute versus relative permittivities. At present the accepted method of calculation is based on the use of formulæ (115) and (116).

114. The elastance of a dielectric between two parallel plates a short distance apart is $S = \sigma\,(l/A)$ where the coefficient σ (sigma) is called the **elastivity of the dielectric.** If S is in megadarafs (1 daraf is the reciprocal of 1 farad) and the dimensions in centimeters, σ is in megadarafs per centimeter cube. Elastance is the reciprocal of permittance, or $S = 1/C$, and, likewise, elastivity is the reciprocal of permittivity, or $\sigma = 4\pi/k$ Therefore

$$S = \left(\frac{4\pi}{k}\right)\frac{l}{A} = \sigma\,\frac{l}{A} \qquad (119)$$

For air, in practical units,

$$\sigma = 11.31 \times 10^6 \text{ mgd. per centimeter cube.} \qquad (120)$$

Example; to calculate the capacity of a plate condenser (Fig. 16) built according to the following specifications: The metal plates are 50 cm. by 70 cm. each, placed at a normal distance of 0.3 cm. The dielectric consists of three consecutive layers of insulation, which are 0.12 cm., 0.07 cm. and 0.11 cm. thick. The relative permittivities of the materials are 2, 3 and 5 respectively. Since elastances are added in series (Par. **110**), the total elastance of the condenser is

$$S = [11.3 \times 10^6/(50 \times 70)][0.12/2 + 0.07/3 + 0.11/5]$$
$$= 0.34 \times 10^3 \text{ mgd.}$$

Hence the capacity $C = S^{-1} = 2.94 \times 10^{-3}$ mf.

115. Capacity of concentric cables. For a single-conductor cable with a grounded metal sheath (Fig. 17) the capacity

$$C = \frac{0.03882k}{\log_{10}(b/a)} \quad \text{(mf. per mile) or} \qquad C = \frac{0.02413k}{\log_{10}(b/a)} \quad \text{(mf. per km.)} \qquad (121)$$

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where k is the relative permittivity of the dielectric (Par. 112). The same formula applies for the capacity or permittance between any two concentric cylinders, provided that their axial length is considerable as compared to their radii so that the effect of the ends may be neglected.

116. Graded insulation. When the insulation between two concentric cylinders consists of several concentric layers (Fig. 17), **the elastance of the** cable is:

$$S = C^{-1} = 25.75[k_1^{-1} \log_{10}(b_1/a) + k_2^{-1} \log_{10}(b_2/b_1) + k_3^{-1} \log_{10}(b_3/b_2) + \text{etc.}] \quad \text{(megadarafs per mile)} \quad (122)$$

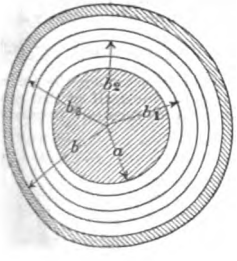


FIG. 17.—Concentric cable.

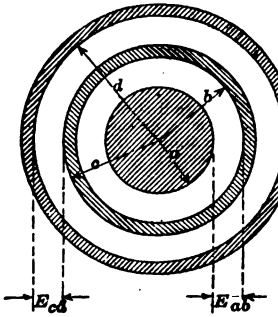


FIG. 18.—Concentric cable and lead sheath.

where k_1, k_2 . . . are the relative permittivities of the layers (Par. 112). The capacity in microfarads per mile is the reciprocal of this expression. The capacity of a cable is directly proportional to its length, while the elastance is inversely proportional to the length.

117. For a single-phase concentric cable with a grounded sheath (Fig. 18), the capacity between two conductors, C_{ab}, and that between the outer conductor and the sheathing, C_{cd}, is calculated according to the formulæ given above. Then, if the voltage between the two conductors is E_{ab} and the voltage between the outer conductor and the sheathing is E_{cd}, the charging current at a frequency of f cycles per second is

$$I = 2\pi f(E_{ab}C_{ab} + E_{cd}C_{cd})10^{-6} \text{ (amp.)}, \quad (123)$$

if C_{ab} and C_{cd} are expressed in microfarads.

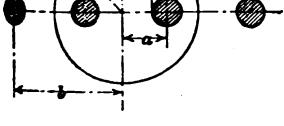


FIG. 19.—Twin conductor cable showing electrical image due to the grounded sheath.

118. Twin-conductor cable with grounded sheath. In this case the sheath may be replaced by a pair of conductors located outside, as shown in Fig. 19. The spacing, b, of these imaginary conductors being given by the relation*

$$ba = d^2 \quad (124)$$

and the **capacity of a single conductor is**

$$C = \frac{0.03882k}{\log_{10}\left[\frac{2a(d^2-a^2)}{r(d^2+a^2)}\right]} \quad \text{(mf. per mile)}. \quad (125)$$

The capacity per mile of the circuit (two miles of conductor) is one-half

* Leo Lichtenstein. *Elek. Zeit.* Vol. XXV, pp. 106 and 124 (1904).

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of the preceding value. The transverse dimensions may be either in inches or in centimeters because only their ratio enters in the formula.

119. A three-conductor cable may be treated in a similar way (Fig. 20). The sheath is replaced by three equally spaced conductors of the same diameter and spaced according to the relation $ba = d^2$. The **capacity of a single conductor** is

$$C = \frac{0.07764k}{\log_{10}\left[\frac{3a^2(d^2-a^2)^2}{r^2(d^6-a^6)}\right]} \quad \text{(mf. per mile)} \quad (126)$$

where the transverse dimensions are in inches or in centimeters.

120. The capacity of a single-phase transmission line per wire, or the permittance between one of the wires and the plane of symmetry is

$$C = \frac{0.03882}{\log_{10}(b/a)} \quad \text{(mf. per mile)} \quad (127)$$

where a is the radius of the wire, and b the spacing between the centres. The capacity between the two conductors is equal to one-half of that given by the formula above. For values of charging current at standard frequencies see tables in Sec. 11.

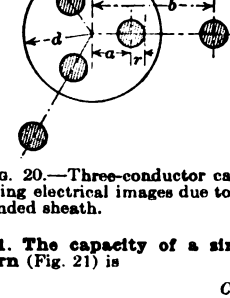


FIG. 20.—Three-conductor cable; showing electrical images due to the grounded sheath.

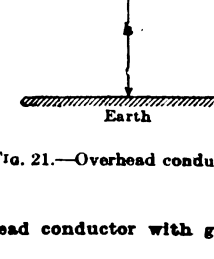


FIG. 21.—Overhead conductor.

121. The capacity of a single overhead conductor with ground return (Fig. 21) is

$$C = \frac{0.03882}{\log_{10}(2h/a)} \quad \text{(mf. per mile)} \quad (128)$$

122. When a single-phase line with metallic return is suspended sufficiently near the ground its capacity is somewhat increased. Let the wires be suspended at the heights h_1 and h_2 above the ground; then calculate the capacity according to formula in Par. **120**, using the corrected spacing (see the author's "Electric Circuit," Art. 61)

$$b_c = \frac{b}{\sqrt{1+(0.25b)^2/h_1h_2}} \quad (129)$$

When the heights of suspension h_1 and h_2 are greater than 3.5 times the spacing b, the difference between b and the corrected spacing b_c is less than 1 per cent. The correction in formula (117) is still smaller, because logarithms of numbers vary more slowly than the numbers themselves.

In formulæ (128) and (129) a perfectly conducting ground is assumed. With dry non-conducting earth the increase in capacity is somewhat less.

123. Capacity of a three-phase line with symmetrical spacing. The concept of the capacity of a three-phase line is not definite without further qualifications. In practice a three-phase line is calculated by reducing it to an equivalent single-phase line consisting of one of the conductors of the three-phase line and a ground return. This equivalent single-phase line carries one-third of the total power transmitted by the three-phase line

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at a voltage $E/\sqrt{3}$ corresponding to the star voltage of the three-phase line. For such an equivalent line the capacity is expressed by the formula given in Par. **120** above, where a is the radius of each wire and b the spacing between the wires. This expression for capacity means that the charging current per wire calculated from the formula $I = 2\pi fCE/\sqrt{3}$ checks with that actually observed in each wire of a three-phase line when a pure sine-wave voltage E is applied between the wires. For values of charging current see tables in Sec. 11.

124. With an unsymmetrical spacing let the actual distances between the three pairs of wires be b_1, b_2, and b_3. The capacity can be calculated from the above given formula **using the equivalent spacing**

$$b_{eq} = \sqrt[3]{b_1 b_2 b_3}, \tag{130}$$

equal to the geometric mean of the actual spacings. For a more detailed treatment of capacity of three-phase lines with unsymmetrical spacing, unsymmetrical voltages and the effect of the ground, see the author's "Electric Circuit," Art. 65. For other formulæ for the capacity of linear conductors and cables see Cohen, L., "Formulæ and Tables for the Calculation of Alternating Current Problems," Chap. 3. See also Fowle, F. F., "The Calculation of Capacity Coefficients for Parallel Suspended Wires," *El. World*, Vol. 58 (1911), pp. 386, 443, and 493.

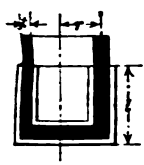


FIG. 22.—Leyden jar.

125. A Leyden jar (Fig. 22) may be considered as a combination of plate condensers. Thus, using the general formula Par. **113**, its **capacity**,

$$C = \kappa \frac{A}{t} = \kappa \frac{\pi r^2 + 2\pi rl}{t} \quad \text{(microfarads)} \tag{131}$$

where the dimensions are in centimeters and $\kappa = 0.08842 \times 10^{-6} k$; see Par. **112**.

126. Permittance of irregular paths. In some cases it is necessary to calculate the capacity of a condenser the dielectric of which is limited by irregular boundaries. The problem is solved either by experiment or by calculations. In performing the experiment the dielectric is sometimes conveniently replaced by a piece of metal of identical shape and with identical terminals. Let the resistance of the metal paths be R, the unknown capacity C, the absolute permittivity of the dielectric k_a (Par. **112**) and the resistivity of the metal ρ (Par. **80**). Then

$$C = \frac{k_a}{R} \rho \tag{132}$$

In order to calculate the permittance without any experiment, various assumptions are made as to the most probable paths of the electrostatic lines of force, and of the various assumptions one is selected which gives the maximum permittance. For details see the author's "Electric Circuit," Arts. 54–55.

127. The energy stored in a condenser. The potential energy stored in a condenser is

$$W = \frac{CE^2}{2} = \frac{Q^2}{2S} = \frac{EQ}{2}, \text{ in joules (watt-seconds)} \tag{133}$$

where the voltage E is in volts, the electrostatic flux (Par. **106**) or charge Q in coulombs, and the capacity C in farads. If C is in microfarads and Q in microcoulombs, W is in microjoules.

128. The density of electrostatic energy, or the energy stored per unit volume of the dielectric, is

$$W' = \frac{k_a G^2}{2} = \frac{D^2}{2k_a} = \frac{GD}{2}, \tag{134}$$

where W' is expressed in microjoules per centimeter cube, k_a is the absolute permittivity of the dielectric in microcoulombs per centimeter cube, and G is the voltage gradient in volts per centimeter length of path; D is the dielectric flux density (Par. **107**) in microcoulombs per square centimeter.

The total energy of an electrostatic field is found by multiplying W' by

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an element of volume ∂s and integrating within the desired limits. For an interesting comparison of practical possibilities as to the amount of energy stored in the dielectric form per unit volume, compared with other forms of energy, see Steinmetz, C. P., *General Electric Review*, 1913, p. 536.

129. A system of charged bodies (Fig. 23). The **total charges** on the individual conductors are expressed by the equations

$$\left.\begin{aligned} q_1 &= C_1v_1 + C_{12}(v_1 - v_2) + C_{13}(v_1 - v_3) + \text{etc.,} \\ q_2 &= C_2v_2 + C_{21}(v_2 - v_1) + C_{23}(v_2 - v_3) + \text{etc.,} \end{aligned}\right\} \quad (135)$$

where v_1, v_2, v_3, etc., are the potentials of these conductors above the ground. The coefficients C_1, C_2, C_3, etc., are called the **partial capacities** of the conductors; C_{12}, C_{23}, etc., are called **mutual capacities.** Their computation is possible in a few simple cases only, but having determined them experimentally, it is possible to calculate from the preceding equations the resultant or equivalent capacity of the system under various operating conditions.

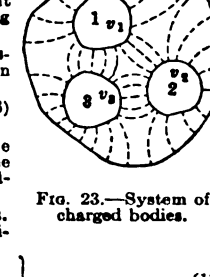


FIG. 23.—System of charged bodies.

130. Maxwell's equations of a charged system. The same equation may be written in Maxwell's form

$$\left.\begin{aligned} q_1 &= K_{11}v_1 + K_{12}v_2 + K_{13}v_3 + \text{etc.,} \\ q_2 &= K_{21}v_1 + K_{22}v_2 + K_{23}v_3 + \text{etc.,} \end{aligned}\right\} \quad (136)$$

where the coefficients K_{11}, K_{22}, etc., are called the capacities of the individual conductors, and the negative quantities K_{12}, K_{23}, etc., are called **coefficients of mutual induction.**

131. Coefficients in Maxwell's equations. The following relations hold between the coefficients K and C:

$$\left.\begin{aligned} K_{11} &= C_1 + C_{12} + C_{13} + \text{etc.} \\ K_{22} &= C_2 + C_{21} + C_{23} + \text{etc.} \\ K_{12} &= -C_{12};\ K_{21} = -C_{21}, \text{ etc.} \end{aligned}\right\} \quad (137)$$

132. The electrostatic energy stored in the field is

$$W = \tfrac{1}{2}K_{11}v_1^2 + \tfrac{1}{2}K_{22}v_2^2 + \text{etc.} + K_{12}v_1v_2 + K_{13}v_1v_3 + K_{23}v_2v_3 + \text{etc.} \quad (138)$$

W is expressed in joules (watt-seconds) if the potentials are in volts and the capacities in farads.

133. The dielectric strength of insulating materials, or the rupturing voltage gradient, is the maximum voltage per unit thickness which a dielectric can stand in a uniform field, before it breaks down electrically. The dielectric strength is usually measured in kilovolts per millimeter or per inch. The only correct way is to refer the dielectric strength to a uniform field, for instance, between large parallel plates placed at a short distance apart. If the striking voltage is determined between two spheres or electrodes of some other shape, the fact should be distinctly stated. In designing insulation a factor of safety is assumed depending upon the conditions of operation. For numerical values of the rupturing voltage gradients of various materials see Sec. 4.

134. The critical dielectric flux density is the density at which the material breaks down. It is determined from the relation

$$D_{max} = 0.08842kG_{max} \times 10^{-2}, \quad (139)$$

where D_{max} is the critical density in microcoulombs per square centimeters G_{max} is the **rupturing voltage gradient** in kilovolts per millimeter, and k is the relative permittivity of the material (Par. **112**).

135. Electrostatic corona. When the electrostatic flux density in the air exceeds a certain value, a pale violet light appears near the adjacent metal surfaces; this silent discharge is called the electrostatic corona. In the regions where the corona appears, the air is electrically broken down, and ionised so that it becomes a conductor of electricity. When the voltage is raised still higher a brush discharge takes place, until the whole thickness of the dielectric is broken down and a disruptive discharge, or spark, jumps from one electrode to the other.

The formation of corona leads to power loss which may be serious in some

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cases (see Sec. 11). Moreover, corona facilitates the formation of nitric acid near the conductors, and may lead to corrosion. When corona is allowed to play on insulation other than air, this insulation may in time be charred and deteriorated. For these reasons it is of importance to know the critical voltages of corona formation and the power loss under various conditions of surfaces, barometric pressure, humidity, etc. The problem is still in a research state. For numerical data in application to transmission lines see Sec. 11; in connection with the design of other high-tension apparatus, Sec. 10.

136. Experiments on corona. A large amount of experimental and theoretical information concerning corona and other allied topics will be found in the various recent volumes of the *Trans.* A. I. E. E. See in particular the valuable papers by F. W. Peek, Jr., H. J. Ryan, and J. B. Whitehead, with the accompanying discussion.

137. Dielectric hysteresis and conductance. When an alternating voltage is applied at the terminals of a condenser, the dielectric is subjected to periodic stresses and displacements. If the material were perfectly elastic, no energy would be lost during one complete cycle, because the energy stored during the periods of increase in voltage would be given up to the circuit when the voltage decreased. In reality, the electric elasticity of solid and liquid dielectrics is not perfect, so that the applied voltage has to overcome some kind of molecular friction, in addition to the elastic forces. The work done against friction is converted into heat, and is lost, as far as the circuit is concerned. This phenomenon is similar to magnetic hysteresis (Par. **89**), and is therefore called *dielectric hysteresis*. The energy lost per cycle is proportional to the square of the applied voltage, because both the displacement and the stress are proportional to the voltage.

An imperfect condenser does not give out on discharge the full amount of energy put into it. After having been discharged and stood some time, an additional discharge may be obtained; this is known as **absorption in the dielectric.**

An imperfect condenser, that is, one which shows a loss of power from one cause or another, can be replaced for purposes of calculation by a perfect condenser with an ohmic conductance shunted around it. This conductance, or "leakance," as some authors call it, is selected of such a value that the I^2R loss in it is equal to the loss of power from all causes in the given imperfect condenser. The actual current through the imperfect condenser is considered then as consisting of two components—the leading reactive component through the ideal condenser, and the loss component, in phase with the voltage, through the shunted conductance. In this way, imperfect condensers can be treated graphically or analytically, according to the ordinary laws of the electric circuit.

TRANSIENT CURRENTS AND VOLTAGES

138. Transient electric phenomena are such as occur between two permanent conditions; for instance, when a load is suddenly changed, an appreciable time elapses before the generators and the line adapt themselves to the new conditions, and the currents and the voltages during the intermediate time are called transient. Some electric phenomena are transient in time (for instance, the short-circuiting of a large alternator), others are transient in space (the distribution of alternating current in solid conductors), and some are transient both in time and in space (surges and traveling waves in long transmission lines).

139. Theory of transient phenomena. The subject is too large and advanced to be treated here in detail. An elementary treatment of the subject will be found in W. S. Franklin's "Electric Waves" and in C. P. Steinmetz's "Electric Discharges, Waves and Impulses." Numerous formulæ and results will be found in Cohen's "Formulæ and Tables for the Calculation of Alternating-current Problems," Chaps. 5 and 6. For a more advanced treatment see J. A. Fleming, "The Propagation of Electric Currents;" A. E. Kennelly, "The Application of Hyperbolic Functions to Electrical Engineering. Problems, "Chap. 6 and foll.; C. P. Steinmetz, "Transient Electric Phenomena and Oscillations." Numerous articles on the subject will be found in the recent volumes of the A. I. E. E., *Elektrotechnische Zeitschrift* and *Archiv fur Elektrotechnik.*

140. Closing a circuit containing a resistance r (ohms) and an inductance L (henrys) in series with a continuous e.m.f. When the de-energized

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circuit is suddenly connected to a source of continuous voltage e, the current gradually rises to the final value $i_o = e/r$ according to the law

$$i = i_o(1 - \epsilon^{-tr/L}), \tag{140}$$

where t is time, and ϵ is the base of natural (or hyperbolic) logarithms. This expression is known as **Helmholtz's law.** When the source of e.m.f. is short-circuited the current in the remaining circuit decreases to zero according to a similar law

$$i = i_o\epsilon^{-tr/L}. \tag{141}$$

141. Periodic e.m.f. When a de-energized circuit containing r and L is suddenly connected at the instant $t = 0$, to a source of alternating voltage $e = E_m \sin(2\pi ft + \alpha)$, the current in the circuit varies according to the law

$$i = \frac{E_m}{z}\sin(2\pi ft + \alpha - \phi) - \frac{E_m}{z}\sin(\alpha - \phi)\epsilon^{-tr/L} \tag{142}$$

In this equation $z = \sqrt{r^2 + (2\pi fL)^2}$ is the impedance of the circuit and ϕ is the phase displacement between the current and the voltage, determined by $\tan\phi = 2\pi fL/r$. The angle α is the phase displacement between the voltage e and the reference wave which passes through zero at the time $t = 0$; f is the frequency. The first term in the expression for i is the current corresponding to the permanent condition, the second term is a transient which rapidly approaches zero with the time. (See also Eq. 146.)

142. Closing a circuit containing a resistance r (ohms) and a capacity C (farads) in series. The charging current is theoretically expressed by

$$i = i_o\epsilon^{-t/(rC)}, \tag{143}$$

where i_o is the current at the first instant. This equation is not applicable to the beginning of the charge because it presupposes a sudden jump of the current from zero to i_o. In reality, the unavoidable inductance of the circuit smoothes down the initial change in current.

When a condenser, charged at a voltage e_o, is discharged through resistance r, the discharge current at the first instant is theoretically equal to $i_o = e_o/r$, and then varies according to the law

$$i = i_o\epsilon^{-t/(rC)} \tag{144}$$

The voltage across the condenser terminals decreases according to a similar law

$$e = e_o\epsilon^{-t/(rC)} \tag{145}$$

When a de-energised circuit containing r and C is suddenly connected at the instant $t = 0$ to a source of alternating voltage $e = E_m \sin(2\pi ft + \alpha)$, the current in the circuit will vary according to the law

$$i = \frac{E_m}{z}\sin(2\pi ft + \alpha + \phi) - \frac{E_m}{z}\sin(\alpha + \phi)\epsilon^{-t/(rC)} \tag{146}$$

In this equation $z = \sqrt{r^2 + [1/(2\pi fC)]^2}$ is the impedance of the circuit, and ϕ is the phase displacement between the current and the voltage, determined by $\cot\phi = 2\pi fCr$. The angle α is the phase displacement between the voltage e and the reference wave which passes through zero at the time $t = 0$; f is the frequency. The first term in the expression for i is the current corresponding to the permanent condition, the second term is a transient which rapidly approaches zero with the time. Compare Par. **141.**

143. Single-energy and double-energy transients. The two preceding cases are examples of single-energy transients, because the energy is stored in one form only (electromagnetic or electrostatic), and the energy change consists in an increase or a decrease of the stored energy. In the case of inductance the energy is that of the magnetic field and in the case of capacity it is the energy of the electrostatic field. When both inductance and capacity are present, the energy of the circuit is stored in two forms and there is a possibility of periodic transformation of the magnetic energy into the dielectric energy, and *vice versa*, which constitutes electric oscillations, surges, and waves. There is also a possibility of a **triple-energy transient**, when for instance a synchronous motor is hunting at the end of a long transmission line which possesses inductance and capacity. In the la

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case the total energy of the system is stored not only in the magnetic and the dielectric forms, but in mechanical form as well.

144. The general differential equation of a circuit containing a resistance r ohms, inductance L henrys and capacity C farads in series, is

$$L\frac{d^2i}{dt^2}+r\frac{di}{dt}+\frac{1}{C}i=\frac{de}{dt}, \tag{147}$$

where e is the voltage applied to the circuit, and t is time.

When the impressed e.m.f. e is constant ($de/dt=0$), two conditions may arise: $r^2>4L/C$ and $r^2<4L/C$. The intermediate or critical case $r^2=4L/C$ is of academic interest only.

145. Non-oscillatory case. In the first case ($r^2>4L/C$) the current in the circuit is non-oscillatory. It rises from zero, reaches a maximum, and falls again to zero when the condenser is fully charged; the current never reverses. The voltage across the condenser gradually rises from zero to its full value, equal to the applied e.m.f., but never exceeding the latter. During the discharge both the current and the voltage across the condenser gradually decrease to zero according to a logarithmic (exponential) law. In practice, these conditions are usually harmless, and therefore desirable in cases where oscillations must be suppressed. This is usually done by increasing the resistance of the circuit until the condition $r^2>4L/C$ is fulfilled.

146. Oscillatory case. In the second case, when $r^2<4L/C$, the charge and also the discharge are oscillatory. The oscillations are of decreasing amplitude, because of the damping caused by the energy consumption in the resistance. When the condenser is charging, the current is

$$i=\frac{2e}{q}\,\epsilon^{-rt/2L}\sin\frac{q}{2L}t, \tag{148}$$

and the voltage across the condenser terminals is

$$e_1=e\left\{1-\epsilon^{-rt/2L}\left(\cos\frac{q}{2L}t+\frac{r}{q}\sin\frac{q}{2L}t\right)\right\}. \tag{149}$$

For condenser discharge

$$i=-\frac{2e_0}{q}\epsilon^{-rt/2L}\sin\frac{q}{2L}t, \tag{150}$$

and

$$e_1=e_0\epsilon^{-rt/2L}\left\{\cos\frac{q}{2L}t+\frac{r}{q}\sin\frac{q}{2L}t\right\}. \tag{151}$$

In these expressions $q=\sqrt{(4L/C)-r^2}$; e is the applied voltage, and e_0 is the voltage across the condenser at the beginning of the discharge; ϵ is the base of natural logarithms.

147. The frequency of oscillation and the logarithmic decrement. The frequency of oscillations in the preceding case is

$$f=\frac{q}{4\pi L}\qquad\text{(cycles per sec.)} \tag{152}$$

When the resistance is negligible, that is, r^2 small compared with $4L/C$, the frequency of oscillations is approximately equal to

$$f_0=\frac{1}{2\pi\sqrt{LC}}. \tag{153}$$

Logarithmic decrement. Successive half waves of oscillations decrease the more in amplitude, the greater the resistance. The ratio of the amplitudes of successive half waves, or the decrement of the oscillation, is $\epsilon^{-rt_1/2L}$ where $t_1=1/(2f)$ is the duration of one-half cycle.

148. Continuous high-frequency oscillations are conveniently produced by use of a direct-current arc (Duddell). In the Poulsen arc, the anode is copper and the cathode carbon, while the arc is formed in an atmosphere of hydrogen, which appears to increase considerably the intensity of the oscillations. Oscillations have been produced of frequencies ranging as high as one million per second and of considerable power; they are

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successfully used for wireless telegraphy. See Poulsen, V., "System for Producing Continuous Electric Oscillations," *Trans.* Int. Elec. Congress, St. Louis, 1904, Vol. II, p. 963. Also Austin, L. W., "The Production of High-frequency Oscillations from the Electric Arc," *Bulletin* of the Bureau of Standards, Vol. III (1907), p. 325.

149. Stored energy. When a considerable amount of energy is liberated at some point on a transmission line, for instance due to an indirect lightning stroke, a wave starts along the line carrying this energy to the ends of the line. Part of it enters the apparatus at the ends, part is reflected and the rest is converted into heat. Generally speaking, the total energy stored in the line, or in some part of it, at an instant is

$$W = \tfrac{1}{2}Li^2 + \tfrac{1}{2}Ce^2, \quad \text{(joules)} \tag{154}$$

where L is the inductance of the line in henrys, i an instantaneous current, C the capacity of the line in farads, and e an instantaneous voltage. The term $\frac{1}{2}Li^2$ represents the electromagnetic energy, the term $\frac{1}{2}Ce^2$ the electrostatic energy. At certain instants the current is equal to zero, at others the voltage is zero, so that the two energies must be equal. Therefore

$$\frac{e_{max}}{i_{max}} = \sqrt{\frac{L}{C}}. \quad \text{(ohms)} \tag{155}$$

Thus, knowing the maximum voltage e_{max}, the largest instantaneous current i_{max} can be calculated, and *vice versa*. For instance, in the case of a lightning stroke, the maximum voltage is limited by the disruptive strength of the insulation to instantaneous voltages, and the maximum current disturbance may be calculated from the preceding equation.

150. Surge impedance. With concentrated inductance and capacity, the frequency of oscillations is (Par. **147**)

$$f_o = \frac{1}{2\pi\sqrt{LC}}. \tag{156}$$

With **uniformly distributed inductance and capacity, the frequency is**

$$f_o' = \frac{1}{4\sqrt{LC}}. \tag{157}$$

The expression $\sqrt{L/C}$ is called **the natural impedance or the surge impedance of the line,** and its reciprocal **the natural admittance or the surge admittance.** For further information consult the references in Par. **139** above.

ALTERNATING-CURRENT CIRCUITS

151. Sine-waves. In this treatment of alternating-current circuits, a sine-wave is arbitrarily assumed. For non-sinusoidal currents and voltages see Par. **190** and following. Beginning with non-inductive circuits, i.e., circuits which contain only resistance, the current at any instant is proportional to the instantaneous value of the impressed e.m.f. Plotting the instantaneous values of the e.m.f. and the current, it is seen, Fig. 24, that the waves pass through zero and reach their maximum values at the same instant. They are said to be **in phase.**

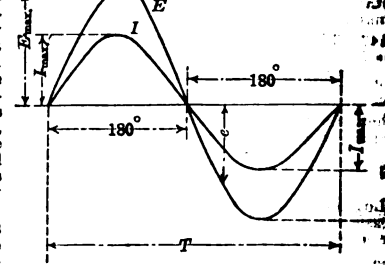


FIG. 24.—Simple sine-waves; non-inductive circuit.

152. Instantaneous values. Let the amplitude or the instantaneous maximum value of the voltage be E_{max}, then the instantaneous value is

$$e = E_{max} \sin 2\pi ft \tag{158}$$

where f is the frequency in cycles per second, and t is time in seconds. The angle $2\pi ft$ is in radians. If the time of one complete cycle is T (Fig. 24), $f = 1/T$.

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153. Reactive e.m.f. In a circuit which contains **inductance** only (Par. 97) the current wave lags by 90 electrical degrees, or a quarter of a cycle, behind the applied e.m.f. Numerically

$$E_x = 2\pi fLI \tag{159}$$

where E_x and I are the root-mean-square or the effective values (**160**) of the voltage and the current respectively, L is the inductance in henrys, and f is the frequency in cycles per second. A similar relation holds true for the amplitudes of voltage and current, or for the average values.

154. Inductive reactance. For the sake of abbreviation, the expression $2\pi fL$ is denoted by x and is called inductive reactance, so that

$$x = 2\pi fL = \frac{E_x}{I} \qquad \text{(ohms)} \tag{160}$$

If L is in henrys and f in cycles per second, x is in ohms, being equal to the ratio of the reactive voltage to the current. If the voltage is expressed as in Par. **152**, the instantaneous current is

$$i = -\frac{E_{max}}{x}\cos 2\pi ft, \tag{161}$$

in other words, the current wave lags 90 deg. in phase behind the voltage wave when the circuit contains inductance only.

155. E.m.f. components. In a circuit which contains resistance and inductance in series, one portion of the impressed e.m.f. may be considered as consumed in resistance drop and another in the counter-e.m.f. of inductive reactance. The flux interlinked with the circuit is in phase with the current which produces it. The e.m.f. generated in the reactance is proportional to the rate of change of the flux, and since the rate of change of the flux is greatest when the value passes through zero, the e.m.f. is in time-quadrature with the flux and therefore also in time-quadrature with the current (Fig. 25).

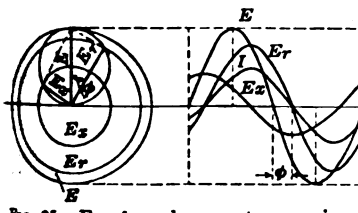


FIG. 25.—E.m.f. and current waves in a circuit containing resistance and reactance in series.

156. Resultant e.m.f. The current is always in phase with the e.m.f. which is consumed in resistance, and the impressed e.m.f. is the resultant of the instantaneous values of the components consumed in resistance and in the inductive reactance. Referring to Fig. 25, E_r is consumed in resistance, E_x is consumed in overcoming the counter-e.m.f. of inductive reactance, and E is the resultant or impressed e.m.f.

157. Phase angle. The current is in phase with E_r but lags behind the impressed e.m.f. E by the **phase angle** ϕ determined from the relation

$$\tan\phi = \frac{2\pi fL}{r} = \frac{x}{r}. \tag{162}$$

If the instantaneous applied voltage is expressed as in Par. **152**, the instantaneous current is

$$i = I_{max}\sin(2\pi ft - \phi) \tag{163}$$

where both $2\pi ft$ and ϕ are expressed either in radians or in degrees. For the numerical relation between E and I see Par. **165** below.

158. Capacity reactance or condensance. In a circuit which contains electrostatic capacity or permittance only, Par. **108**, the current wave leads the applied voltage by 90 electrical degrees, or is in leading quadrature with it. Numerically

$$E_c = x_c I \tag{164}$$

where

$$x_c = \frac{1}{2\pi fC} \qquad \text{(ohms)} \tag{165}$$

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is called **capacity reactance**, or **condensive reactance**. When **inductive reactance** x (Par. **154**) and **condensive reactance** x_c enter in the same circuit, x_c is considered negative. When C is in farads, x_c is in ohms. See Par. **241**.

159. E.m.f. components. **In a circuit containing resistance and condensive reactance in series,** the applied e.m.f. may be divided into two components; one consumed in resistance drop and the other in the condensive reactance. The current taken by the condensive reactance is proportional to the rate of change of the e.m.f., which is impressed across its terminals, therefore the counter-e.m.f. of the condensive reactance is in time-quadrature with the current. Referring to Fig. 26, I is the total current in phase with E_r which is the e.m.f. consumed in resistance; E_c is the voltage necessary to balance the counter-e.m.f. of the condensive reactance, and E is the total e.m.f. impressed upon the circuit. It will be seen that in this case the current is leading.

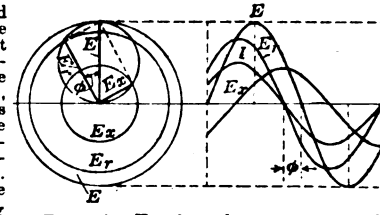


FIG. 26.—E.m.f. and current waves in a circuit containing resistance and capacity reactance in series.

If the instantaneous applied voltage is expressed as in (**152**), the instantaneous current is

$$i = I_{max} \sin (2\pi ft + \phi). \tag{166}$$

In this expression, the **phase angle** ϕ between the current and the voltage is determined from the relation

$$\tan \phi = \frac{1}{2\pi fCr} = \frac{x_c}{r}. \tag{167}$$

160. Terminology. The following terminology used in application of **sine-wave alternating-current circuits** is recapitulated here for the sake of convenience. An **instantaneous value** of alternating current or voltage (Fig. 24) is connected with the **maximum value** or the **amplitude** by the relation given in Par. **152**. The **mean effective value**, also called the **root-mean-square value**, or simply the **effective value of** an alternating current or voltage is defined in Par. **199**. For a sine-wave quantity the effective value is equal to the amplitude divided by $\sqrt{2}$; or

$$E_{eff} = \frac{E_{max}}{\sqrt{2}} = 0.7071 E_{max}. \tag{168}$$

The **mean or average value** of a sinusoidal alternating current or voltage is equal to the maximum value divided by $\pi/2$, or

$$E_{ave} = \frac{2E_{max}}{\pi} = 0.6366 E_{max}. \tag{169}$$

The ratio between the effective and the average value is called the **form factor** (Par. **207**) and is equal to 1.11 for sine-waves.

161. Periodic time. The interval of time T in Fig. 24. corresponds to one complete cycle. The interval of time $T/2$ corresponding to one-half wave is called an **alternation**, and for every cycle there are two alternations. The **frequency** or the **periodicity** of an alternating current may be expressed either in cycles per second or in alternations per minute. However, the latter method is not common.

162. The phase displacement between two currents or two voltages, or between a current and a voltage, is commonly measured in **electrical degrees.** One electrical degree is 1/360th part of a complete cycle.

163. Vector representation. Alternating currents and voltages which vary according to the sine or cosine law can be represented graphically by directed straight lines called **vectors** (Fig. 27). The length of a vector represents, to some arbitrary scale, the effective value of the alternating

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quantity, while the position of the vector with respect to a selected reference vector gives the phase displacement. *Counter-clockwise direction of rotation is always considered positive*, so that for instance in the diagram (*b*) the voltage leads the current by 90 deg. By means of vectors the relative phase position and value of either currents or e.m.fs. can be represented in the same manner as forces in mechanics.

164. Vector diagrams for simple series circuits. Referring to Fig. 27, diagrams are shown for circuits containing (*a*) resistance; (*b*) inductive reactance; (*c*) condensive reactance; (*d*) resistance and inductive reactance; (*e*) resistance and condensive reactance; (*f*) resistance, inductive reactance and condensive reactance.

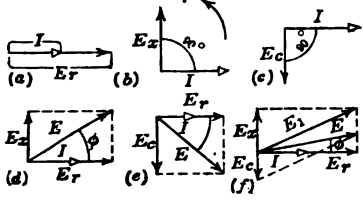


FIG. 27.—Vector diagram of current and e.m.f.; series circuits.

165. Ohm's law for alternating-current circuits. The **impedance** (in ohms) is the ratio of an alternating voltage E across a part of a circuit to the current I through the circuit. Denoting the impedance by z,

$$E = zI, \qquad (170)$$

where E and I are the effective values. This equation expresses only the numerical relations; it must be remembered that E and I are not in phase with one another.

166. Impedance consisting of resistance and reactance in series. In a circuit containing an ohmic resistance r in series with an inductive reactance x (Par. **156**) the impedance is numerically

$$z = \sqrt{r^2 + x^2}, \qquad (171)$$

so that numerically,

$$I = \frac{E}{\sqrt{r^2 + x^2}}. \qquad (172)$$

The **phase angle**, by which the current lags behind the voltage, is found from the relation

$$\tan \phi = \frac{x}{r}, \text{ or } \cos \phi = \frac{r}{z}. \qquad (173)$$

167. Impedance consisting of resistance and condensance in series. In a circuit containing an ohmic resistance r in series with a condensive reactance x_c (Par. **159**), similar relations hold, in which x_c is substituted for x. The current leads the voltage and the angle ϕ is to be considered as negative.

168. Impedance consisting of resistance, reactance and condensance in series. If a circuit contain both inductive and condensive reactance (Fig. 27*f*), the impressed e.m.f. is

$$E = \sqrt{E_r^2 + (E_x - E_c)^2} = \sqrt{(Ir)^2 + (Ix - Ix_c)^2}. \qquad (174)$$

Dividing E by I, the impedance is

$$z = \sqrt{r^2 + (x - x_c)^2}. \qquad \text{(ohms)} \qquad (175)$$

where

$$x = 2\pi fL = \omega L \qquad \text{(see Par. 154)} \qquad (176)$$

$$x_c = \frac{1}{2\pi fC} = \frac{1}{\omega C} \qquad \text{(see Par. 158)} \qquad (177)$$

169. Current components; parallel circuits of resistance and reactance. The current, like the e.m.f., can be split into two components, one in phase and the other in quadrature with the e.m.f. It is convenient to employ the e.m.f. diagram with series circuits and the current diagram with parallel circuits. A current diagram is presented in Fig. 28. It presupposes a non-inductive resistance r connected in parallel with a pure inductive reactance x. The total current

$$I = \sqrt{I_r^2 + I_x^2} \qquad \text{(amp.)} \qquad (178)$$

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If E is the voltage across the circuit, then

$$I_r = E\left(\frac{r}{r^2+x^2}\right) = Eg \quad \text{(amp.)} \quad (179)$$

$$I_x = E\frac{x}{r^2+x^2} = Eb \quad \text{(amp.)} \quad (180)$$

$$I = \sqrt{(Eg)^2+(Eb)^2} = E\frac{1}{z} = Ey \quad \text{(amp.)} \quad (181)$$

In these expressions

$$g = \frac{r}{z^2} = \text{conductance} \quad \text{(mho)} \quad (182)$$

$$b = \frac{x}{z^2} = \text{susceptance} \quad \text{(mho)} \quad (183)$$

$$y = \frac{1}{z} = \text{admittance} \quad \text{(mho)} \quad (184)$$

$$\tan\phi = \frac{I_x}{I_r} = \frac{b}{g};\ \cos\phi = \frac{I_r}{I} = \frac{g}{y}. \quad (185)$$

170. Resistance and condensance in parallel. In a circuit consisting of a resistance and a capacity in parallel the same relations hold except that the current is leading, and x_c is used in place of x (Par. **158**). If there is any doubt whether the quadrature current is caused by an inductance or a capacity, use the expressions inductive susceptance and capacity (or condensive) susceptance. The latter is sometimes called **capacitance**. Fig. 28 also shows, in dotted lines, the resultant current when a pure resistance and a pure condensance are connected in parallel; in such case the phase angle ϕ becomes an angle of lead.

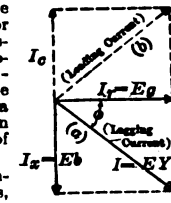


FIG. 28.—Vector diagram of currents; resistance in parallel (a) with inductive reactance; (b) with capacity reactance.

171. Impedances in series. In a circuit containing several resistances and reactances in series, the resistances should be added together and the reactances added together, so that

$$\left.\begin{aligned} r_{eq} &= \Sigma r; \\ x_{eq} &= \Sigma x; \end{aligned}\right\} \quad (186)$$

$$z_{eq} = \sqrt{(\Sigma r)^2+(\Sigma x)^2}. \quad (187)$$

The subscript eq stands for equivalent.

172. Impedances cannot be added algebraically, but must always be added geometrically, or vectorially. Since

$$r = z\cos\phi, \text{ and } x = z\sin\phi, \quad (188)$$

the preceding equation gives

$$z_{eq} = \sqrt{(\Sigma z\cos\phi)^2+(\Sigma z\sin\phi)^2}. \quad (189)$$

173. Admittances in parallel. In a circuit consisting of several parallel branches the conductances should be added together and the susceptances added together (Par. **169**) so that,

$$\left.\begin{aligned} g_{eq} &= \Sigma g \\ b_{eq} &= \Sigma b \end{aligned}\right\} \quad (190)$$

and

$$y_{eq} = \sqrt{(\Sigma g)^2+(\Sigma b)^2}. \quad (191)$$

174. Admittances cannot be added algebraically, but must always be added geometrically, or vectorially. Since

$$g = y\cos\phi, \text{ and } b = y\sin\phi, \quad (192)$$

the preceding equation gives

$$y_{eq} = \sqrt{(\Sigma y\cos\phi)^2+(\Sigma y\sin\phi)^2}. \quad (193)$$

175. Equivalent series and parallel combinations. Let r_s and x_s be a resistance and a reactance connected in series and let r_p and x_p be a

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resistance and a reactance connected in parallel. The two combinations are called equivalent when a given impressed alternating voltage produces the same total current through both, in magnitude and in phase. In other words, both combinations must have the same impedance z (or admittance y), and the same phase angle ϕ. The two resistances and the two reactances are connected by the relations

$$\left.\begin{aligned} r_s r_p &= z^2 = \frac{1}{y^2}; \\ x_s x_p &= z^2 = \frac{1}{y^2}; \end{aligned}\right\}$$

and also

$$\left.\begin{aligned} g &= \frac{r_s}{z^2}, \quad b = \frac{x_s}{z^2}; \\ r_s &= \frac{g}{y^2}, \quad x_s = \frac{b}{y^2}. \end{aligned}\right\} \tag{194}$$

176. Calculation of series-parallel circuits. The foregoing relations are useful in determining the voltage and current relations obtaining in complex series-parallel circuits. For example, in the circuit shown in Fig. 29 the resistance r_1 in series with reactance x_1 is replaced by a conductance $g_1 = r_1/z_1^2$ in parallel with a susceptance $b_1 = x_1/z_1^2$, where

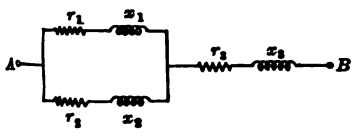


Fig. 29.—Series-parallel combination.

$$z_1^2 = r_1^2 + x_1^2. \tag{195}$$

A similar substitution is made for the branch 2, then the branches 1 and 2 are replaced by one equivalent branch of conductance $g_4 = g_1 + g_2$ in parallel with the susceptance $b_4 = b_1 + b_2$. Now the branch g_4, b_4, is replaced by an equivalent series combination consisting of a resistance $r_4 = g_4/y_4^2$ in series with a reactance $x_4 = b_4/y_4^2$, where

$$y_4^2 = g_4^2 + b_4^2. \tag{196}$$

The original series-parallel combination is thus reduced to a simple series circuit, and we finally have

$$\left.\begin{aligned} r_{eq} &= r_3 + r_4, \\ x_{eq} &= x_3 + x_4. \end{aligned}\right\} \tag{197}$$

Knowing r_{eq} and x_{eq} the total current may be found for a given voltage or *vice versa*, from the relations given in Par. 166.

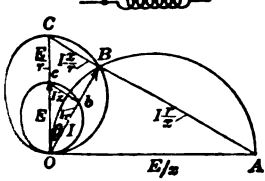


Fig. 30.—Circle diagram for series circuits.

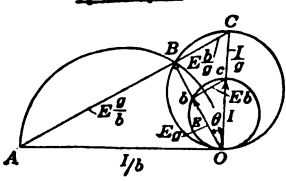


Fig. 31.—Circle diagram for parallel circuits.

177. Circle diagram; series circuits. Drs. F. Bedell and A. C. Crehore developed a circle diagram which shows the interrelation of the various constants in an alternating-current circuit when one or more quantities are varied.

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Considering the series circuit shown in Fig. 30, let it be required to study the current when the resistance and reactance are varied, the e.m.f. being kept constant. With E as a diameter draw the circle, *Obc*, then *Obc* is the e.m.f. or impedance triangle and θ is the angle of phase displacement between I and E. Dividing the current, I, into imaginary components, E/r is laid off along OC in phase with E, and E/x is laid off along OA in quadrature with E. Drawing the line AC, and the circles, OBA and OBC, the line, OB, represents the current, I, both as to value and phase position. If x is constant and r variable, the point, B, will travel along the circle, OBA, while if r is constant and x variable, the point, B, will travel along the circle, OBC.

178. Circle diagram; parallel circuits. Referring to the parallel circuit in Fig. 31, let it be required to study the e.m.f. when the conductance and susceptance are varied, the current remaining constant. With I as diameter draw the circle *Obc*, then *Obc* is the current or admittance triangle and θ is the angle of phase displacement between E and I. Dividing the e.m.f. into components, I/b is laid off along OA in quadrature with I; then drawing the line, AC, and the circles, OBA and OBC, the line, OB, represents the e.m.f., E, both as to value and phase position. The circle, OBA, is the locus of the point, B, when b is constant and g variable, while the circle, OBC is the locus of the point, B, when g is constant and b variable.

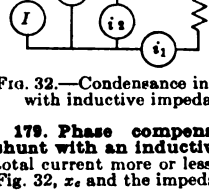


FIG. 32.—Condensance in parallel with inductive impedance.

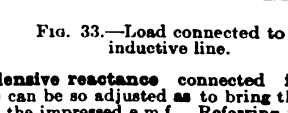


FIG. 33.—Load connected to inductive line.

179. Phase compensation. Condensive reactance connected in **shunt with an inductive impedance** can be so adjusted as to bring the total current more or less in phase with the impressed e.m.f. Referring to Fig. 32, x_c and the impedance z_s are in parallel, where

$$z_s^2 = r^2 + x_s^2. \tag{198}$$

Taking the admittances,

$$g_1 = \frac{r}{z_s^2}; \; g_2 = 0; \; b_1 = \frac{x_s}{z_s^2}; \text{ and } b_2 = -\frac{1}{x_c}. \tag{199}$$

In order that I be in phase with E, $b_1 + b_2$ must be equal to zero, or

$$x_c = \frac{z_s^2}{x_s} \tag{200}$$

Thus, it is seen that the value of x_c depends upon the resistance, r, as well as upon x_s:

$$i_2 = E\frac{1}{x_c} = Eb_2; \; i_1 = E\sqrt{\left(\frac{r}{z_s^2}\right)^2 + \left(\frac{x_s}{z_s^2}\right)^2} = E\sqrt{g_1^2 + b_1^2}, \tag{201}$$

$$I = E\sqrt{\left(\frac{r}{r^2+x_s^2}\right)^2 + \left\{\left(\frac{x_s}{r^2+x_s^2}\right) - \frac{1}{x_c}\right\}^2} = E\sqrt{g^2+b^2}, \text{ in amp.} \tag{202}$$

180. Leading current through an inductive line will raise the e.m.f. at the receiving end of the circuit. Referring to Fig. 33, let E be the voltage at the generator end of a circuit, e the voltage at the receiver end, and i the line current. Let the load be of such a nature that the current is leading with respect to the voltage e. Adding to e the ohmic drop ir in the line (Fig. 34*a*) in phase with i, and the reactive drop ix in leading quadrature with i, the impressed voltage E is obtained. It will be seen that $E < e$; but with a lagging current, $E > e$ (Fig. 34*b*).

181. Series resonance. In a constant-potential circuit which contains inductive reactance and also condensive reactance in series, it is possible

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to obtain an enormous rise in e.m.f. by adjusting the reactances or the frequency. Thus, according to Par. **168**,

$$E = Iz = I\sqrt{r^2+(x_s-x_c)^2}, \qquad \text{(volts)} \qquad (203)$$

The e.m.f. across the condensive reactance is

$$e = Ix_c,$$

so that

$$\frac{e}{E} = \frac{x_c}{\sqrt{r^2+(x_s-x_c)^2}} = \frac{x_c}{z}. \qquad (204)$$

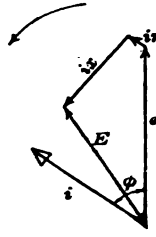


FIG. 34a.—Effect of inductance with leading current.

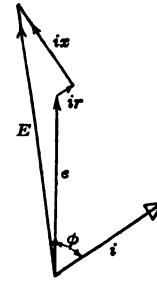


FIG. 34b.—Effect of inductance with lagging current.

Now, z (the total impedance) may be less than x_s, and in this case e (the drop across the condenser terminals) will be greater than E (the total impressed e.m.f.). If the frequency is

$$f = \frac{1}{2\pi\sqrt{LC}}, \qquad \text{(cycles per second)} \qquad (205)$$

we shall have

$$x_s = x_c, \qquad (206)$$

which condition gives the highest rise in voltage. If moreover r (the resistance of the circuit) is assumed to be zero,

$$\frac{e}{E} = \infty, \qquad (207)$$

and we have an extreme case of **voltage resonance.**

This is purely an ideal case, but in any event

$$\frac{e}{E} = \frac{x_c}{r} \text{ when } f = \frac{1}{2\pi\sqrt{LC}}; \qquad (208)$$

wherein L is the coefficient of self-induction in henrys and C the capacity in farads of the apparatus connected in series. Sometimes the constants of the circuit are such that a resonance of one of the higher harmonics of the voltage takes place.

183. Parallel resonance. When an inductive reactance and a condensive reactance are joined together in parallel, they can be so adjusted or the frequency can be so chosen that **current resonance** will take place.

Let the total conductance of the combination be g, the inductive susceptance b_s, and the condensive susceptance b_c. Then, the total current

$$I = Ey = \sqrt{g^2+(b_s-b_c)^2} \qquad (209)$$

The current through the condensive susceptance is

$$i_c = Eb_c, \qquad (210)$$

so that

$$\frac{i_c}{I} = \frac{b_c}{\sqrt{g^2+(b_s-b_c)^2}} = \frac{b_c}{y}. \qquad (211)$$

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But the total admittance y may be smaller than b_c, and in this case the tota line current I is less than one of its components i_c. A similar relation may be proved for i_s. When the frequency is

$$f = \frac{1}{2\pi\sqrt{LC}}, \qquad \text{(cycles per second)} \qquad (212$$

it follows that

$$b_s = b_c, \qquad (213$$

and

$$I = Eg, \quad i_c = -i_s. \qquad (214$$

The line current is comparatively small, but there is a large interchang of current between the inductance and the capacity, in parallel.

Resonance can occur at only one frequency. Sometimes, in the cas of a complex wave, it occurs at the frequency of one of the componen harmonics instead of the fundamental frequency. In such case, either fo voltage or current (series or parall resonance), the magnitude of the reso nant harmonic component is much exag gerated, as compared with its norma magnitude in a non-resonant circuit The condition of resonance, except i tuned circuits where it is specially de sired (as in radio-telegraphy), is one t be avoided.

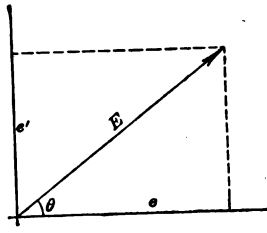


FIG. 35.—Complex quantities; axes of reals and imaginaries.

183. Consonance. Resonance i the primary circuit of a transformer caused by the proper combination c inductance and capacity in the second ary circuit, is called consonance.

184. Alternating currents and voltages treated by means of com plex (imaginary) quantities. If and e' (Fig. 35) are the projections o the components of a vector E along two perpendicular axes, then the vecto E may be represented symbolically as

$$\dot{E} = e + je', \qquad (215$$

where

$$j = \sqrt{-1}, \qquad (216$$

and the dot under E signifies that the magnitude as well as the directio of E is meant.

185. Addition and subtraction of vectors. Let two vectors of volt age be represented as

$$\dot{E}_1 = e_1 + je'_1, \qquad (217$$

$$\dot{E}_2 = e_2 + je'_2. \qquad (218$$

Then the sum or the difference of these two vectors is

$$\dot{E}_3 = \dot{E}_1 \pm \dot{E}_2 = (e_1 \pm e_2) + j(e'_1 \pm e'_2). \qquad (219$$

186. Rotation of a Vector. Multiplying a vector by j turns it by 90 deg. in the positive direction (counter-clockwise). Thus,

$$j\dot{E} = j(e + je') = -e' + je \qquad (220$$

because $j^2 = -1$. Multiplying a vector by $-j$ rotates the vector by 90 deg in the negative direction—that is, clockwise.

A vector E may be also represented symbolically (Fig. 35) as

$$\dot{E} = E(\cos\theta + j\sin\theta) \qquad (221$$

where E without the dot, on the right hand side of the equation, stands for the magnitude only.

The operator

$$\epsilon^{j\phi} = \cos\phi + j\sin\phi, \qquad (222$$

where ϵ is the base of natural logarithms, turns a vector by the angle ϕ in the positive direction. Thus,

$$E(\cos\phi + j\sin\phi) = E(\cos\theta + j\sin\theta)(\cos\phi + j\sin\phi) = E[\cos(\theta+\phi) + j\sin(\theta+\phi). \qquad (223$$

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The operator

$$e^{-j\phi} = \cos\phi - j\sin\phi \tag{224}$$

turns a vector by the angle ϕ in the negative direction, that is, clockwise.

187. Impedance and admittance operators. The impedance operator

$$Z = r + jx \tag{225}$$

converts the vector of a current into that of a potential difference across an impedance (consisting of a resistance r in series with a reactance x). **The admittance operator**

$$Y = g - jb \tag{226}$$

converts the vector of a voltage applied across the terminals of a conductance g in parallel with a susceptance b, into the vector of the total current through this combination. When b stands for capacity susceptance, as in a transmission line (Par. **236**), $Y = g + jb$. When a current $\dot{I} = i + ji'$ flows through the impedance $Z = r + jx$, the required voltage is

$$\dot{E} = Z\dot{I} = (r + jx)(i + ji'), \tag{227}$$

or, separating the real and the imaginary quantities,

$$\dot{E} = (ir - i'x) + j(i'r + ix). \tag{228}$$

In other words, $\dot{E}$ is a vector such that its horizontal projection e (Fig. 35) is equal to $(ir - i'x)$, and the vertical projection is $(i'r + ix)$.

The angle θ which $\dot{E}$ forms with the horizontal axis is determined by

$$\tan\theta = \frac{(i'r + ix)}{(ir - i'x)}. \tag{229}$$

188. Networks of conductors. The method given in Par. **29** to **35** is generalized in the case of alternating e.m.fs. by writing Kirchhoff's equations for the vectors of the currents and of the voltages. With the notation used above, we have

$$\Sigma\dot{I} = 0; \quad \Sigma\dot{E} = \Sigma\dot{I}Z. \tag{230}$$

Equating the vertical and the horizontal projections of the vectors to zero separately (Fig. 35), and using expression (228), equations (230) become

$$\left.\begin{array}{l} \Sigma i = 0; \ \Sigma i' = 0; \\ \Sigma(ir - i'x) = \Sigma e; \\ \Sigma(i'r + ix) = \Sigma e'. \end{array}\right\} \tag{231}$$

If there are n unknown currents or voltages, $2n$ independent equations of the form (231) may be written, and from these equations $2n$ projections of n unknown vectors can be determined. The problem is thus similar to that with direct currents, and the references given in Par. **35** may be consulted for simplifications which may be taken advantage of in practical cases.*

189. The expressions for power and power factor. The average power expressed through the projections of the vectors is

$$P = ei + e'i' = EI\cos\phi, \tag{232}$$

where e and e' are the projections of the voltage E (Fig. 35), and i and i' are those of the current I. Note that the power is not a vector quantity.

The power factor is found from the relation

$$\cos\phi = \cos(\theta_e - \theta_i), \tag{233}$$

where

$$\theta_e = \tan^{-1} e'/e \text{ and } \theta_i = \tan^{-1} i'/i. \tag{234}$$

Or else, the angle ϕ is found directly from the relation

$$\tan\phi = [(e'/e) - (i'/i)]/[1 + (e'i'/ei)] \tag{235}$$

If $\tan\phi$ is positive, the current is lagging; otherwise it is leading—with respect to the e.m.f. See also Par. **196**.

*See also Campbell, G. A. "Cisoidal Oscillations;" *Trans.* A. I. E. E., Vol. XXX, 1911, pp. 873 to 913.

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NON-SINUSOIDAL OR COMPLEX WAVES

190. Examples of complex waves. The curves shown in Fig. 3 illustrate the effect of the inductance and the capacity in a circuit to whic is applied an alternating e.m.f., differing from the simple sine-wave. Th curves were taken simultaneously with an oscillograph. E is the impresse e.m.f.; I_s the current taken by an inductance coil, and I_c that taken by condenser. Fig. 37 shows the circuit.

191. Wave of reactive e.m.f. due to inductive reactance. Assumir the reluctance of the iron core the inductance coil to be constan which is approximately true belo the saturation point, the value



FIG. 36.—Complex alternating-current waves.

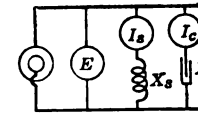


FIG. 37.—Circuit in which th waves of Fig. 36 were observed

the flux is proportional to the current I_s. The instantaneous value of th e.m.f. E (see Par. **67**) is

$$e = n\frac{d\phi}{dt} = L\frac{di}{dt} \qquad (23$$

that is, the curve E will have its maximum amplitude when the curve passes through zero. This is not exactly true in this case, because of small loss in the resistance and the iron; the current to supply this lo being in phase with the e.m.f. E.

192. Wave of current through condensive reactance. The condens current is proportional to the rate of change of the e.m.f. (see Par. **166** the instantaneous value is

$$i_c = C\frac{de}{dt}, \qquad (237$$

that is, the curve, I_c, has its maximum when the rate of change of the curv E, is a maximum. Were E a sine curve, I would be also a sine curve an would be in quadrature with E, but when the curve of e.m.f. is not a sir curve, as in Fig. 36, the maximum amplitude of the current will occur at th point where the slope of the e.m.f. curve is a maximum.

193. Effects of inductive and condensive reactance on wave form These curves show the effect upon the current wave form of inductiv reactance and condensive reactance. The curve, E, is the wave for produced by the generator; it contains several harmonics (see Par. **209**). Th inductive reactance tends to damp out the higher harmonics, while th condensive reactance emphasizes them.

194. Determination of total complex current wave. When th applied voltage contains higher harmonics (Par. **209**) the total cu rent through an impedance is found by summing the harmonic current due to each harmonic of the voltage acting alone. Thus, the reactanc at the fundamental frequency f is $x_1 = 2\pi fL$, the reactance to the nt harmonic is $x_n = 2\pi nfL$, and the impedance to the nth harmonic is

$$z_n = \sqrt{r^2 + (2\pi nfL)^2}. \qquad (23$$

195. Power and energy. The general expression for the energy deliv ered to an alternating-current circuit with any wave form of current an voltage is

$$W = \int_{t_1}^{t_2} eidt \text{ (joules or watt-seconds)}, \qquad (23$$

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where e is an instantaneous value of the voltage in volts, i is the corresponding instantaneous current in amperes and $t_2 - t_1 = T$ is the interval of time, in seconds, for which the energy is to be determined. The average power delivered during the same interval is

$$P = \frac{1}{t_2 - t_1} \int_{t_1}^{t_2} ei\,dt \qquad \text{(watts)} \qquad (240)$$

196. Power factor, sine-waves. When the current and the voltage vary according to the sine law, the power $P = IE \cos \phi$, where E and I are the effective values of the voltage and the current respectively, and ϕ is the phase angle between the two, $\cos \phi$ being known as the power factor of the circuit. See also Par. **189.**

197. Power factor, complex waves. When e and i are irregular curves, the average power is found as the average ordinate of a curve, the ordinates of which are proportional to the product ei. If e and i are resolved into their harmonics, each harmonic contributes its own share of power as if it were acting alone, so that the average power is

$$P = E_1 I_1 \cos \phi_1 + E_3 I_3 \cos \phi_3 + \text{etc.}, \qquad (241)$$

where I_1, I_3, etc., and E_1, E_3, etc., are the effective values of the harmonic currents and voltages respectively, and the angles ϕ are the respective phase displacements.

198. The energy component and the reactive component of voltage or current. In a simple harmonic circuit with the voltage E, current I, and the phase displacement ϕ between the two, $E \cos \phi$ is called the energy component of the voltage and $E \sin \phi$ the reactive component of the voltage. Analogously, $I \cos \phi$ is the energy component of the current and $I \sin \phi$ is the reactive component of the current. Similar components are used in circuits with non-sinusoidal currents and voltages, provided that these are first replaced by equivalent sine-waves.

199. Effective value of any wave. The effective value of a variable current or voltage is defined as that continuous value which gives the same total i^2r loss. Or, if I be the effective value of a variable current i,

$$I^2rT = \int_0^T i^2r\,dt \qquad \text{(joules)}$$

from which

$$I = \sqrt{\frac{1}{T} \int_0^T i^2 dt} \qquad \text{(amp.)} \qquad (242)$$

This may be expressed by saying that the *effective value of a current or voltage is equal to the square root of the mean square (r.m.s.) of the variable values.* Hot-wire instruments and electrodynamometer-type instruments indicate directly the effective values of alternating currents and voltages.

200. Effective value of a sine-wave. For sine-waves the effective values are given in Par **160.** In terms of the maximum value, the effective value is $E_{eff} = 0.7071\ E_{max}$.

201. Computation of effective value of a complex wave; first method. For irregular waves the following **four methods** are used in order to obtain the effective value of the ordinates of a curve, $y = f(x)$. Under the first method, plot a curve the ordinates of which are equal to y^2. Determine the average ordinate of this curve either by a planimeter or by weighing the paper on which it is drawn, and take the square root of the value of this ordinate.

202. Second method. According to **Simpson's rule,**[*] divide the curve

[*] Simpson's Rule is a formula for computing the area comprised between a given curve, $y = f(x)$, the axis of abscissæ and two given ordinates. Divide the distance between the given ordinates into n equal parts, where n is an even number, and erect the corresponding ordinates. Let these ordinates,

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into k equal parts by $k+1$ equidistant ordinates y_0, y_1, etc., y_k, where k is an even number. Then the effective value is

$$y_{eff} = \frac{1}{\sqrt{3k}}\left[y_0^2+4(y_1^2+y_3^2+\text{etc.}+y_{k-1}^2)+2(y_2^2+y_4^2+etc+y_{k-2}^2)+y_k^2\right]^{\frac{1}{2}}. \quad (243)$$

203. Third method. If the irregular wave is given in terms of its harmonics, then the effective value is

$$y_{eff} = 0.7071\sqrt{A_1^2+A_3^2+\text{etc.}}, \quad (244)$$

where A_1, A_3, etc., are the amplitudes of the separate harmonics.

204. Fourth method. Replot the given irregular curve (Fig. 38) in polar coordinates (Fig. 39), and determine the area A_p, of the polar curve with a planimeter, or by plotting on homogeneous paper of known area and weight, then cutting out and weighing again; the areas are then proportional

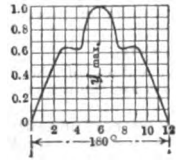


FIG. 38.—Complex wave in rectangular coordinates.

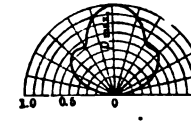


FIG. 39.—Complex wave of Fig. 38 in polar coordinates.

to the weights. This area must be expressed in units, y^2_{max}, as taken from Fig. 38. This is done by multiplying the area, A_p, of the polar curve by the ratio $\left(\frac{y_{max}}{\rho_{max}}\right)^2$; y_{max} and ρ_{max} are measured in terms of the same units. The mean effective ordinate is

$$y_{eff} = \frac{y_{max}}{\rho_{max}}\sqrt{\frac{2A_p}{\pi}}, \qquad \text{in terms of } y_{max}. \quad (245)$$

205. Generalization of fourth method. The latter method has been generalized by Mr. C. O. Mailloux for determining the effective value of direct current taken by an electric car or a train during a run. For a detailed treatment and numerous practical applications see his paper "Methode de Determination du Courant Constant Produisant le Même Echauffement qu'un Courant Variable," in the Transactions of the International Electrical Congress held at Turin (Italy), 1911.

206. The amplitude factor is the ratio of the maximum ordinate to the mean effective ordinate, thus

$$\frac{y_{max}}{y_{eff}} = \text{amplitude factor}. \quad (246)$$

207. The form factor is the ratio of the mean effective ordinate to the mean ordinate, thus

$$\frac{y_{eff}}{y_{mean}} = \text{form factor}. \quad (247)$$

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including the two given ones, be denoted y_0, y_1, y_2, etc., y_n. Then the area of the curve is

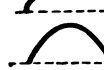
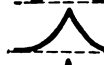
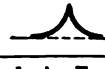
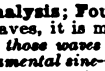
$$A = \tfrac{1}{3}h[y_0+4(y_1+y_3+y_5+\text{etc.}+y_{n-1})+2(y_2+y_4+y_6+\text{etc.}+y_{n-2})+y_n],$$

where h is the distance between any two adjacent ordinates. The greater the number of strips (n), the more nearly the foregoing formula represents the area of the given curve.

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The table in Par. **208** gives the form factor and the amplitude factor for various mathematical curves.

208. Table of Form Factors and Amplitude Factors.

Name.	Trace.	Form factor.	Reciprocal of form factor.	Amplitude factor.	Reciprocal of amplitude factor.
Rectangle		1.00	1.00	1.00	1.00
Semi-ellipse		1.04	0.96	1.22	0.82
Semi-circle		1.04	0.96	1.22	0.82
Semi-ellipse		1.04	0.96	1.22	0.82
Sine		1.111	0.900	1.414	0.707
Triangle		1.15	0.87	1.73	0.58
Inverse sine		1.31	0.76	2.10	0.48
Inverse circle or inverse ellipse		1.44	0.69	3.23	0.31

209. Wave analysis; Fourier's series. In the mathematical treatment of alternating waves, it is most convenient to work with those having sine form: therefore, *those waves differing from the sine form are generally resolved into both a fundamental sine-wave and its harmonics.* The general equation of any alternating wave, as given by Fourier's series, is

$$y = Y_1 \sin(\omega t + \theta_1) + Y_2 \sin(2\omega t + \theta_2) + \ldots + Y_n \sin(n\omega t + \theta_n) + \text{etc.}, \quad (248)$$

wherein y is the ordinate of the resultant wave; Y_1, Y_2, . . . Y_n, etc., are the maximum ordinates of the first, second, . . . nth, etc., harmonics; θ_1, θ_2, . . . θ_n, the constant angles which determine the relative time-phase position of the corresponding harmonics, and $\omega = 2\pi f$ the angular velocity of the generating vector of the fundamental wave.

210. Wave analysis; Fischer-Hinnen's method. By inspection it can be said that waves having like loops above and below the time axis contain only odd harmonics, while waves having unlike loops above and below the axis contain both even and odd harmonics. A direct method of wave analysis given by J. Fischer-Hinnen* is based on the following equations:

$$A_n = \frac{1}{n}(y_6 + y_8 + y_{12} + \ldots y_{2n-2} - y_2 - y_4 - y_{10} - \ldots y_{2n-4}) \quad (249)$$

and

$$B_n = \frac{1}{n}(y_1 + y_5 + y_9 + \ldots y_{2n-1} - y_3 - y_7 - y_{11} - \ldots y_{2n-3}) \quad (250)$$

wherein y_1, y_2 . . . y_n are ordinates at points along the base of the half wave, which is divided into $2n$ equal parts, and A_n and B_n are the ordinates of the nth harmonics lying 90 time-degrees apart. The maximum ordinate of the nth harmonic is $\sqrt{A_n^2 + B_n^2}$, and its time phase displacement from the resultant wave is

$$\theta_n = \tan^{-1}\left(\frac{A_n}{-B_n}\right), \quad (251)$$

* *Elek. Zeit.*, Vol. XXII, p. 396 (1901). Also P. M. Lincoln, *Elec. Jour.*, Vol. V, p. 286 (1908).

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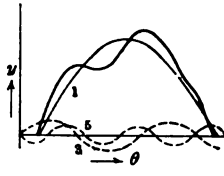
θ_n being measured in terms of the nth harmonic. Assuming time measured t the right and ordinates measured up as positive, and quantities measure in opposite directions as negative, positive values of θ_n indicate that th nearest intersection of the nth harmonic with the axis is to the right of th intersection of the resultant wave with the axis, and positive values of θ indicate that the nth harmonic is rising at its nearest intersection with th time axis. The values obtained with the above equations for the nt harmonic are affected by the harmonics which are multiples thereof, that $2n$, $3n$, etc. This correction is practically negligible for all harmonics, excep the first or fundamental, and a correction rarely needs to be carried beyon the ninth harmonic. Since wave forms in practice almost never conta even harmonics, they do not enter into the correction, and denoting th corrected values by prime, we have:

$$A'_n = A_n - A'_{3n} - A'_{5n} - A'_{7n} - \quad . \quad . \quad . \tag{25}$$

and

$$B'_n = B_n + B'_{3n} - B'_{5n} + B'_{7n} - \quad . \quad . \quad . \tag{25}$$

When applying this to the first harmonic, A_n is the ordinate of the r sultant wave at y_0 (Fig. 40b), and B_n is the ordinate 90 time-degrees ther from at y_3.



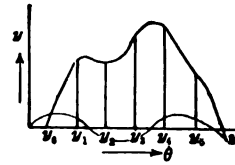


FIG. 40a.—Wave analysis, Par. 211. FIG. 40b. Wave analysis, Par. 21

211. Example of wave analysis. As an example,* assume the wa given in Fig. 40a, which is split into three harmonics; the first or fund mental, the third and the fifth. Fig. 40b shows the method of determini a given harmonic, in this case the third. The base of the wave is divide into $2n$ or six equal parts and ordinates erected. Assume the ordinates measure as follows:

$$y_1 = 676;\ y_2 = 660;\ y_3 = 940;\ y_4 = 1004;\ y_5 = 554;\ y_6 = 0. \tag{25}$$

then,

$$A_3 = \tfrac{1}{3}(y_4 - y_2) = \frac{1004 - 660}{3} = 114.7, \tag{25}$$

and

$$B_3 = \tfrac{1}{3}(y_1 + y_5 - y_3) = \frac{676 + 554 - 940}{3} = 96.7. \tag{25}$$

The maximum ordinate is

$$\sqrt{(114.7)^2 + (96.7)^2} = 150 \tag{25}$$

and the phase angle is

$$\theta_3 = \tan^{-1}\left(\frac{-114.7}{96.7}\right) = -50 \text{ deg.}\dagger \tag{25}$$

In a similar manner it is found that $A_5 = -92.8$, and $B_5 = 37.4$. In t example the wave contains only the third and the fifth harmonics; therefo the fundamental is determined as follows:

$$A_1 = y_0 - A'_3 - A'_5 = 0 - 114.7 + 92.8 = -21.9;$$
$$B_1 = y_3 + B'_3 - B'_5 = 940 + 96.7 - 37.4 = 999.3;$$
$$\theta_1 = \tan^{-1}(21.9/999.3) = 1 \text{ deg. } 15 \text{ min. (approx.)}$$

* *Elec. Jour.*, Vol. V, p. 386 (1908).

† Fifty deg. in the terms of the third harmonic, or 50/3 deg. in terms the resultant

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212. Wave analysis tables are available (Published by John Wiley and Sons, inc.,) by means of which an irregular wave may be easily analyzed into its harmonics by taking a sufficient number of ordinates. For the use of these tables see the author's "Experimental Electrical Engineering," Volume II, Chapter 31; John Wiley and Sons, New York, 1911.

POLYPHASE SYSTEMS

213. A polyphase system is an alternating-current circuit or network in which are applied two or more e.m.fs. of the same frequency, but displaced in phase by a fixed amount relatively to one another.

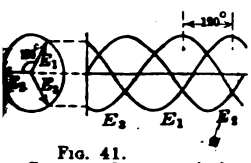


FIG. 41.

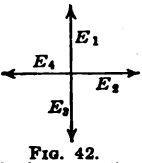


FIG. 42.

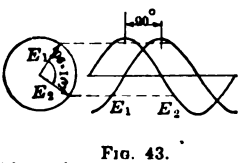


FIG. 43.

FIG. 41.—Symmetrical polyphase e.m.f's. (three-phase system).
FIG. 42.—Symmetrical polyphase e.m.f's. (quarter-phase system).
FIG. 43.—Unsymmetrical polyphase e.m.f's. (two-phase system).

214. Symmetry of polyphase systems. A polyphase system is called symmetrical if the applied voltages are equal and displaced in phase by equal amounts. The three-phase system (Fig. 41) and the quarter-phase system (Fig. 42) are symmetrical systems; the two-phase system (Fig. 43) is an unsymmetrical system.

215. A balanced polyphase system is one in which the sum total of the instantaneous power in all the phases is constant (non-pulsating). Thus, in a symmetrical three-phase system in which an equal load is applied to all the three phases, the power is constant, notwithstanding the fact that the power in each phase is pulsating.

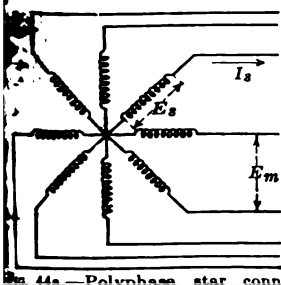


FIG. 44a.—Polyphase star connection.

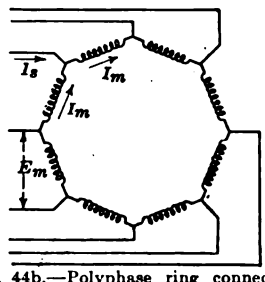


FIG. 44b.—Polyphase ring connection.

216. Balance factor. If the total power in a polyphase system is pulsating, the system is called unbalanced; the ratio of the instantaneous minimum value of power to the maximum value of power is called the balance factor of the system.

217. Star and ring connections. The two principal methods of connecting the separate phases of a polyphase system are the star connection (Fig. 44*a*), and the ring or **mesh** connection (Fig. 44*b*). In a symmetrical n-phase system, with the phases equally loaded, the relation between the star voltages E_s and the mesh (or ring) voltages E_m (Fig. 45*a*)

$$E_m = 2E_s \sin \frac{\pi}{n} \qquad (259)$$

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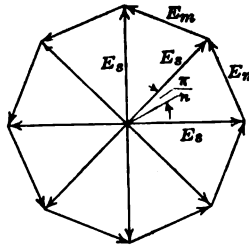


FIG. 45a.—Symmetrical star and ring e.m.fs.

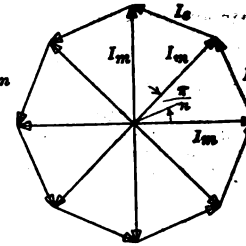


FIG. 45b.—Symmetrical star and ring currents.

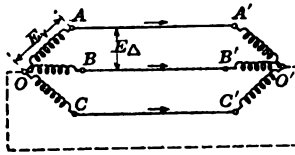


FIG. 46a.—Three-phase Y connection.

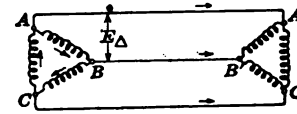


FIG. 46b.—Three-phase delta connection.

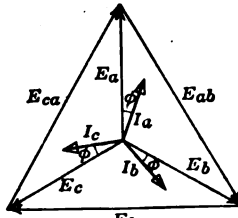


FIG. 47a.—Three-phase Y e.m.fs. and currents.

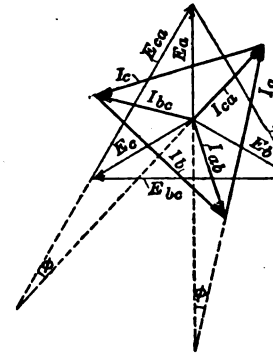


FIG. 47b.—Three-phase Δ e.m.fs. and currents.

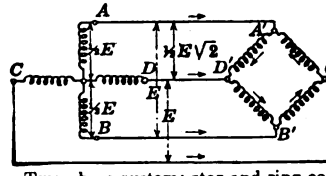


FIG. 48.—Two-phase system; star and ring connections.

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The relation between the star currents I_s and the mesh currents I_m (Fig. 45b) is

$$I_s = 2I_m \sin \frac{\pi}{n}. \qquad (260)$$

218. Three-phase Y and Δ connections. In a three-phase system the star connection is also called the Y-connection (Fig. 46a), and the mesh is called the delta connection (Fig. 46b). The relations of the currents and the voltages are (Figs. 47a and 47b).

$$E_{\Delta} = E_y\sqrt{3} = 1.732E_y, \text{ and } I_{\Delta} = \frac{I_y}{\sqrt{3}} = \frac{I_y}{1.732}. \qquad (261)$$

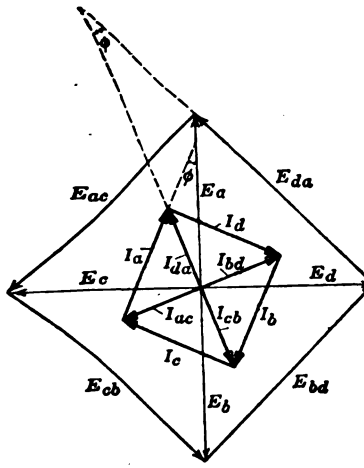


FIG. 49.—Two-phase e.m.fs. and currents.

219. Two-phase star and ring connections. In a two-phase system (Fig. 48) the relations of the currents and the voltages are (Fig. 49)

$$E_m = E_s\sqrt{2} = 1.414E_s; \quad I_m = \frac{I_s}{\sqrt{2}} = \frac{I_s}{1.414} = 0.7071I_s \qquad (262)$$

where the subscripts m and s refer to the mesh and the star respectively (Par. 217)

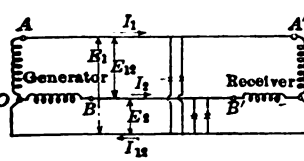


FIG. 50.—Two-phase three-wire system.

220. Two-phase three-wire system. With a two-phase three-wire system (Fig. 50) the current in the common or return wire is $\sqrt{2}$ times the current in each phase (Fig. 51), and the voltage between the phases is $\sqrt{2}$ times the voltage between each phase and the common return.

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221. Polyphase power. The total power in a **symmetrical** *n*-pha **system** is given by the formula

$$P = nI_s E_s \cos\phi = nI_m E_m \cos\phi. \quad (26$$

In an **unsymmetrical** or **unbalanced system** the **total power** is fou by summing up the power in the separate phases.

222. Three-phase power. In a three-phase system (Fig. 46), the pow

$$P = 3I_y E_y \cos\phi = 3I_\Delta E_\Delta \cos\phi = I_y E_\Delta \sqrt{3} \cos\phi \quad \text{(watts)} \quad (26$$

if the currents are in amperes and the voltages in volts.

223. Two-phase power. In a **quarter-phase system** (Fig. 47) t power

$$P = 4I_s E_s \cos\phi = 4I_m E_m \cos\phi = 2\sqrt{2} I_s E_m \cos\phi \quad \text{(watts)} \quad (26$$

224. An equivalent single-phase circuit is a circuit which is used computations relating to polyphase transmission lines and machine For three-phase circuits some engineers use a single-phase circuit with a voltage equal to the Y-voltage of the three-phase system, and the power equal to that in one phase. Others use a single-phase circuit having a voltage equal to the delta voltage of the three-phase circuit, and transmitting the power equal to the total power in the three phases. Both methods lead to the same result, provided that the assumptions are consistently carried out.

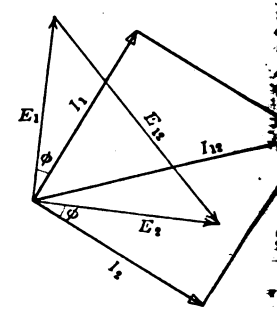


FIG. 51.—E.m.fs. and currents i two-phase three-wire system.

225. Unbalanced polyphase circuits are treated as separate single-phase circuits and then combined into one. Assuming a three-phase system with a line voltage triangle as shown in Fig. 52 and an unbalanced load, E_1, E_2 and E_3, are given. (They form the triangle *abc*.) Constructing semicircles on E_1, E_2, and E_3 as diameters, the e.m.f. triangle for each branch is constructed (Par. 155). We have

$$\frac{E_1}{z_1} = i_1, \quad \frac{E_2}{z_2} = i_2 \text{ and } \frac{E_1}{z_3} = i_3. \quad (2$$

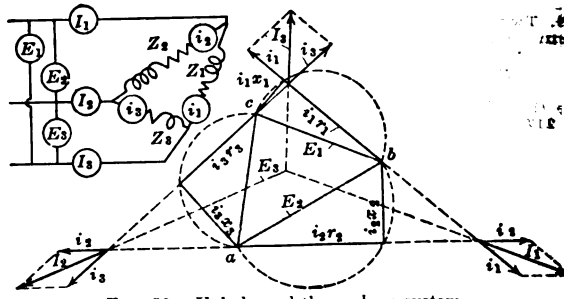


FIG. 52.—Unbalanced three-phase system.

The currents, i_1, i_2 and i_3, are in phase with the *ir* drops in their respect branches. These can be conveniently combined by prolonging the *ir* li until they intersect, and laying off the currents, *i*, from the intersecti The main currents, I_1, I_2 and I_3, are found by taking the vector sum of t branch currents, i_2 and i_3, i_3 and i_1, i_1 and i_2, respectively.

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226. Unbalanced star-connected system. Let, in Fig. 44*a*, all the star admittances be different from each other, and let the admittances of the branches between the two neutral points be Y_1, Y_2, etc., also all different. Let E_0 be the potential difference between the two neutral points, the vector E_0 being measured in the same direction as the phase voltages E_s. Then the currents in the individual phases are:

$$\left.\begin{aligned} I_1 &= Y_1(E_1 - E_0) \\ I_2 &= Y_2(E_2 - E_0), \text{ etc.} \end{aligned}\right\} \tag{267}$$

where

$$E_0 = \frac{\Sigma Y E}{\Sigma Y} \tag{268}$$

First, E_0 is computed from eq. (268) and then the currents determined from eq. (267). All the quantities in eq. (267) and (268) are understood to be vectors in complex notation (Pars. 184 to 187). When there is a common return conductor of appreciable impedance, the foregoing expressions are still applicable, if the given n-phase system be considered as an $(n+1)$-phase system, the last phase consisting of the return conductor for which $E_s = 0$.

227. Three-phase, unbalanced star-connected system. Some of the special cases of the foregoing formulæ are as follows: (*a*) the load admittances are balanced, the applied voltages unsymmetrical, no common return conductor:

$$E_0 = \tfrac{1}{3}\Sigma E \tag{269}$$

(*b*) same, with a return conductor of admittance Y_0:

$$E_0 = \frac{\Sigma E}{3 + (Y_0/Y)} \tag{270}$$

(*c*) When the load admittances are unequal, the general equations (267) and (268) must be used, whether the voltages are balanced or not.

228. Resolution of an unbalanced three-phase system into two balanced systems. It is sometimes convenient to represent a given system of three unequal delta voltages as a result of superposition of two balanced systems of voltages of opposite phase sequence. This is expressed symbolically by the vectorial equations:

$$\left.\begin{aligned} E_1 &= A + B \\ E_2 &= Aa + Ba^{-1} \\ E_3 &= Aa^{-1} + Ba \end{aligned}\right\} \tag{271}$$

In these equations E_1, E_2, E_3 are the given unbalanced voltages, and A and B are the component vectors which together make vector E_1. The factor $a = e^{j2\pi/3}$ turns a vector in the positive direction (counter-clockwise) by 120 degrees (Par. 186). It will thus be seen that the balanced A-system has its vectors numbered counter-clockwise, while the vectors in the B-system are numbered clockwise. Only two of the three equations are independent because

$$E_1 + E_2 + E_3 = 0 \tag{272}$$

229. Determination of the balanced components. When E_1, E_2, and E_3 are given, we have from eq. (271)

$$\left.\begin{aligned} A &= \frac{E_2 - E_1 a^{-1}}{a - a^{-1}} \\ B &= \frac{E_1 a - E_2}{a - a^{-1}} \end{aligned}\right\} \tag{273}$$

When the principle of superposition is applicable, that is in circuits without saturation, the currents may be determined for the systems A and B separately, using the simple relationships (Par. 218) which hold for a balanced system, and then added to obtain the actual currents. For details, applications, and an extension to n phases, see C. L. Fortescue, *Trans.* A. I. E. E., 1918, Vol. 37, p. 1027; J. Slepain, *Electrical World*, 1920, Vol. 75, p. 313.

230. Higher harmonics in polyphase systems. In a balanced n-phase system the time angle between two consecutive star voltages is $2\pi/n$. If the voltage wave has a q-th harmonic, the angle between the phases of these harmonics will be $2\pi q/n$. When $q = n$, $3n$, $5n$, etc., the q-th harmonics

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in all the voltages are in phase with each other. When the neutral poi of the system are isolated, such harmonics give rise to the so-called **oscill ing neutral.** With the grounded neutrals, currents of the correspond frequency flow through all the phases and return through the ground. the three-phase system the harmonic voltages in phase with one another the 3rd, the 9th, the 15th, etc.

231*a*. Harmonics in mesh voltages. Harmonics of the order n, $3n$, etc., even if present in the star voltages, cannot appear in the mesh volta Thus, in a balanced three-phase system, harmonics of the following order absent in delta voltages: 3rd, 9th, 15th, etc., although they may exist in s voltages and in the line currents, and may give rise to inductive interfere and to other troubles.

231*b*. Harmonics in mesh and star currents. In a mesh or ring (F 44*b*) the harmonic currents of the order $q = n$, $3n$, $5n$, etc. (Par. **230**) are phase with one another and may cause large circulating currents, even thou they are absent in the line currents.*

232. For further treatment of the current and voltage relatio with unbalanced loads and unsymmetrical voltages see the last f chapters, in Dr. Steinmetz's "Alternating-current phenomena"; also author's "Experimental Electrical Engineering," Vol. II, Chapter 25, a his "Ueber mehrphasige Stromsysteme bei ungleichmässiger Belastun (Enke, Stuttgart, 1900). For the "V" and "T" connections of tra formers, and for six-phase connections, see Sec. 6, on transformers. Also Sec. 11, on Power Transmission, for further treatment of the calculation polyphase systems, and Sec. 12, on Distribution Systems.

UNIFORMLY DISTRIBUTED RESISTANCE, REACTANCE, CAPA ITY AND LEAKAGE

233. Uniformly distributed properties. In a **transmission line resistance,** the **reactance,** and the **capacity** are **uniformly distribute** Besides, there may be appreciable **leakage** to the ground or between wires, which leakage for the purposes of computation may also be assum to be uniformly distributed. Under such conditions the current along line at any certain instant is different in different places; in other words, current is a function not only of time t but also of the distance s from receiver end.

234. Continuous impressed e.m.f. For a **direct-current li** possessing a resistance of r ohms per unit length and a leakage conductan of g mhos per unit length, the current and the voltage relations at a distan s from the receiver end are expressed by the differential equations,

$$\frac{d^2i}{ds^2} = rgi, \text{ and } \frac{d^2e}{ds^2} = rge. \quad (27$$

The solution of these equations is of the form

$$i = A_1\epsilon^{-ms} + A_2\epsilon^{ms}, \quad (27$$

$$e = B_1\epsilon^{-ms} + B_2\epsilon^{ms}; \quad (27$$

where $m = \sqrt{rg}$, and A_1, A_2, B_1 and B_2, are the constants of integration whi are determined by the electrical conditions at some one point of the line.

235. Solution of continuous-current case. The solution of the for going differential equations is preferably expressed through **hyperbol functions,**† in the form

$$i = C_1 \text{ Cosh } ms + C_2 \text{ Sinh } ms; \quad (27$$

$$e = D_1 \text{ Cosh } ms + D_2 \text{ Sinh } ms; \quad (27$$

* For a detailed treatment see V. Karapetoff, "Harmonics in Symmetric *M*-phase Systems," *Electrical World*, 1918, Vol. 71, p. 660.

† For a simple theory of hyperbolic functions see Seaver's "Mathematic Handbook," Sec. III; also somewhat more advanced, "Hyperbolic Fun tions," by McMahon. The best tables of hyperbolic functions of re hyperbolic angles are probably those by Becker and van Orstrand, publishe by the Smithsonian Institution. Tables of hyperbolic functions of com plex angles over a limited range will be found in the above-mentioned boo McMahon, and also in the *General Electric Review*, Supplement, Ma 1910, and in the *Harvard Engineering Journal*, Vol. X, No. 4 and Vol. I No. 2. See also A. E. Kennelly, "Tables and Chart Atlas of Comple Hyperbolic and Circular Functions," Harvard Univ. Press, 1914.

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where C_1, C_2, D_1, and D_2 are the constants of integration which depend upon the given conditions at some one point on the line. For example, if the receiver current I_2 and the receiver voltage E_2 are given, the constants have the following values:

$$C_1 = I_2;\quad C_2 = E_2\frac{g}{m};\quad D_1 = E_2;\quad D_2 = I_2\frac{m}{g}. \tag{279}$$

Thus, knowing i and e at the receiver end, their values may be calculated for the sending end or for any point on the line. For further details see the first few chapters of A. E. Kennelly's "The Application of Hyperbolic Functions to Electrical Engineering Problems."

Another form of solution, employing the exponential method instead of the hyperbolic, will be found in the *Transactions* of the A. I. E. E.* for 1911, where the problem discussed is one of telegraphic transmission over long aerial-wire circuits by means of the closed-circuit Morse system widely used in America.

236. Alternating impressed e.m.f. Let a sine-wave alternating voltage be applied to an equivalent single-phase line (Par. 224) with uniformly distributed characteristics. Let the resistance and the inductive reactance of the line be r ohms and x ohms per unit length, respectively, so that the series impedance is $Z = r + jx$ ohms per unit length. Let the condensive susceptance and the leakage conductance be b and g mhos, per unit length respectively, so that the shunted admittance is $Y = g - jb$ mhos per unit length. The current and the voltage relations at a distance s from the receiver end of the line are expressed by the differential equations

$$\frac{d^2I}{ds^2} = M^2I, \text{ and } \frac{d^2E}{ds^2} = M^2E \tag{280}$$

where $M = \sqrt{YZ}$. In these expressions I, E and M are complex quantities (Par. 184), and the magnitude and the phase of the current and the voltage vary from point to point, remaining at the same time sine functions. In other words, the current and the voltage are sine functions of time t, and such functions of s as to satisfy the above-given equations. The parameter M characterizes the line and is independent of either t or s. The solution of these equations is of the form

$$I = A_1\epsilon^{-Ms} + A_2\epsilon^{Ms} \tag{281}$$

$$E = B_1\epsilon^{-Ms} + B_2\epsilon^{Ms}, \tag{282}$$

where the constants of integration A_1, A_2, B_1 and B_2 are complex quantities

These constants are determined by the electrical conditions at some one point of the line, for instance, when the current and the voltage at one point are given in magnitude and in relative phase position.

237. Solution of alternating-current case. The solution of the foregoing differential equations is preferably expressed through **hyperbolic functions** (Par. **235**) of the complex angle Ms. Namely,

$$I = C_1 \text{ Cosh } Ms + C_2 \text{ Sinh } Ms; \tag{283}$$

$$E = D_1 \text{ Cosh } Ms + D_2 \text{ Sinh } Ms; \tag{284}$$

where the complex quantities C_1, C_2, D_1, and D_2 are the constants of integration which depend upon the given conditions at some one point of the line.

For example, if the **receiver voltage** E_2 and **the receiver current** I_2 are given in magnitude and in phase (at $s = 0$) the constants of integration have the following values:

$$C_1 = I_2;\ C_2 = E_2\frac{Y}{M};\ D_1 = E_2;\ D_2 = I_2\frac{M}{Y}. \tag{285}$$

Thus, knowing I and E at the receiver end, their values may be calculated for the sending end or at any other point on the line.

238. The general relationship between the currents and the voltages at the two ends of a line of the length l is:

$$I_1 = I_2 \text{ Cosh } Ml + E_2(Y/M) \text{ Sinh } Ml \tag{286}$$

$$E_1 = E_2 \text{ Cosh } Ml + I_2(M/Y) \text{ Sinh } Ml \tag{287}$$

* Fowle, F. F. "Telegraph Transmission;" *Trans.* A. I. E. E., 1911, Vol. XXX, Part II, p. 1683.

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If any two of the four quantities E_1, E_2, I_1, and I_2 are given, the other two may be determined from these two simultaneous equations.

239. Methods of computation. Numerical computations connected with eq. (286) and (287) may be performed in accordance with one of the following methods:

(1) Tables and charts of hyperbolic functions of *complex variables* are available, but the intervals are too large, and the interpolation is both tedious and inaccurate.

(2) Tables of hyperbolic and circular functions of *real angles* are available with much smaller intervals between consecutive values, making the interpolation in most cases unnecessary. When using such tables the following relationships are taken advantage of:

$$\text{Sinh } (a+jb) = \text{Sinh } a \text{ Cos } b + j \text{ Cosh } a \text{ Sin } b \tag{288}$$

$$\text{Cosh } (a+jb) = \text{Cosh } a \text{ Cos } b + j \text{ Sinh } a \text{ Sin } b \tag{289}$$

(3) The hyperbolic functions of the complex angle Ml are expanded into the *infinite series*,

$$\text{Sinh } Ml = Ml + \tfrac{1}{3}(Ml)^3 + \tfrac{1}{120}(Ml)^5 + \text{ etc.} \tag{290}$$

$$\text{Cosh } Ml = 1 + \tfrac{1}{2}(Ml)^2 + \tfrac{1}{24}(Ml)^4 + \text{ etc.} \tag{291}$$

For the longest transmission lines in use or projected, the second term is small as compared to the first, and the third is altogether negligible.

(4) Graphical *approximate solutions*, simplified formulæ, sets of curves, etc., have been proposed at different times for various problems connected with eq. (286) and (287). They refer only to specific applications, such as power transmission, telephone transmission, radio antenna oscillations, etc.

240. References to other literature. For further details and application of the foregoing equations to power-transmission lines and to the propagation of currents in telephone and telegraph lines see C. P. Steinmetz "Theory and Calculation of Transient Electric Phenomena and Oscillations;" J. A. Fleming, "The Propagation of Electric Currents in Telephone and Telegraph Conductors;" F. E. Pernot, "Electrical Phenomena in Parallel Conductors (Wiley).

CAPACITY IN ALTERNATING-CURRENT CIRCUITS

241. In addition to the general information contained in Par. **158–176** the following more specific formulæ are useful in practice.

242. Capacity susceptance. When an alternating-current circuit contains capacity only, the relationship between the current and the voltage (Par. **158**) may be also represented as

$$I_c = b_c E_c \tag{292}$$

where

$$b_c = 1/x_c = 2\pi fC \tag{293}$$

The quantity b_c is called the capacity susceptance, and is measured in mhos when f is in cycles per sec. and C is in farads.

243. Capacity and inductance in parallel. When a capacity C and a pure inductance L are connected in parallel, the **equivalent susceptance** is

$$b = b_s - b_c = \frac{1}{2\pi fL} - 2\pi fC \tag{294}$$

and the total current through the combination is

$$I = bE \tag{295}$$

When $b_s > b_c$ the current lags behind the voltage by 90 deg.; when $b_s < b_c$ the current leads the voltage by 90 deg. See Par. **182.**

244. Capacity in parallel with a conductance. With the notation in Pars. **242** and **19**, the admittance (Par. **169**) of the combination, in mhos, is

$$y = \sqrt{g^2 + b_c^2} = \sqrt{(1/r_p)^2 + (2\pi fC)^2} \tag{296}$$

Thus, an imperfect or **leaky condenser** may be replaced by a perfect condenser with a conductance in parallel, according to formula (296). When r is in ohms, C must be in farads, and not in microfarads.

245. Capacity in series with a resistance. The impedance of the combination, in ohms, is

$$z = \sqrt{r_s^2 + (1/2\pi fC)^2} \tag{297}$$

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246. Equivalent series and parallel combinations of capacity and resistance. The equations given in Par. **178** hold true, provided that the values of capacity susceptance, admittance and impedance are used as given in Pars. **243** to **245**. The equivalent values are also sometimes called the **effective** values of resistance, conductance, reactance and susceptance respectively, although the term equivalent is preferable.

247. Combinations of capacity, inductance and resistance. When the effect of the capacity predominates, the value of its susceptance (when in parallel with the inductance) is corrected for the effect of the inductance (Par. **243**) and the combination is treated as a resistance and a capacity only. Similarly, a correction is made in the value of capacity reactance when an inductive reactance is in series with it. When the effect of the inductance predominates, corrections are made for the capacity effect in the formulas for the inductive reactances or susceptance. See Par. **168**.

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SECTION 3

MEASUREMENTS AND MEASURING APPARATUS

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SECTION 3

MEASUREMENTS AND MEASURING APPARATUS

ELECTRIC AND MAGNETIC MEASUREMENTS

BY F. MALCOLM FARMER, M.E.

GENERAL

1. The measurement of any given quantity is the comparison c that quantity with another quantity of the same kind which has been chose as a unit. The **unit** may be a purely arbitrary quantity with no rationa significance, such as the foot and the pound, or it may have a very definit meaning, as the centimeter and the gram. The units used in electrica measurements belong to the latter class because they are based on the **centi meter-gram-second** or **C.G.S.** system. The C.G.S. system (Sec. 1 is the fundamental system upon which all physical measurements have bee based, on the theory that all physical phenomena are the result of matte and motion, that is, space (centimeters), mass (grams) and time (seconds

2. Measurements classified according to precision.—Electrica measurements may be divided, in a very general way, into three classe (a) **High-precision measurements**, such as those made at the variou national standardizing laboratories in connection with the establishmen and maintenance of standards. Every precaution is observed to obtai the highest possible degree of accuracy. Expense is a secondary consideri tion. (b) **Commercial laboratory measurements**, where the obje is to secure results which are reliable and accurate, but only to the degr justified by commercial and engineering requirements. The cost must b a minimum. (c) **Commercial measurements** are those involved in th production, distribution and sale of energy. The scope of the subject i this section is limited to the last two classes.

3. A standard is a concrete representation of a unit. The fundament C.G.S. units are difficult to represent and early in the development of the a the need for a system of units which could be used in electrical measuremen was recognized, and resulted in the establishment of the "practical" uni (see Sec. 1). These units are derived from the fundamental C.G.S. uni and can be represented by definite, concrete and reproducible standards.

The distinction drawn between primary and secondary standards largely a matter of viewpoint. In general, however, primary standards ma be considered as those which represent directly by definition the unit involve such as the mercury ohm, the silver voltameter and the saturated cadmiu cell, made according to certain specifications. Secondary standards are th more practicable working standards which are standardized by comparis with primary standards and used as the basis of all ordinary measurement They include, for example, the manganin standard resistances and the ord nary Weston-type standard cell. Primary standards are, in general, mai tained only by the government custodians of the standards in the vario countries; whereas secondary or working standards, based on these prima standards, serve as the fundamental basis of practical measurements in en neering and commercial fields.

4. The precision obtainable in an electrical measurement depen upon the various factors which enter into the determination; among the are the correctness of the principle employed and the method used, accura of the standards, number and magnitude of possible errors, correctness calculations and so forth. In precision measurements, as classified abov a precision of one part in 100,000 in certain classes of measurements is reg larly attained. In commercial measurements, the cost of such a high degr

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of precision is not justified. The limits, however, are being gradually raised as the art develops and greater refinements are introduced. The table given in Par. 5 indicates the precision which may be reasonably expected in various classes of measurements made by average observers, under ordinary conditions, and with standard commercial instruments.

5. Table of Average Precision to be Expected in Various Classes of Commercial Measurements

Class of Measurements and Method	Probable precision, per cent.
(Deflections of two-third scale assumed in indicating instruments)	
Current	
Potentiometer, high-grade types	0.03
Portable ammeter, continuous-current	0.4
Portable ammeter, alternating-current	0.5 –1.0*
Switchblard ammeter, continuous-current	1.5
Switchboard ammeter, alternating-current	1.0 –2.5*
Recording instruments	1.5 –3.0
Potential	
Potentiometer, high-grade type	0.02
Portable voltmeter, continuous-current	0.25
Portable voltmeter, alternating-current	0.5 –1.5*
Switchboard voltmeter, continous-current	1.0
Switchboard voltmeter, alternating-current	1.0 –2.5*
Recording instruments	1.5 –3.0
High potentials (in testing of insulators, etc.)	5.0
Power	
Portable wattmeters	1.0
Laboratory wattmeters (non-portable or semi-portable)	0.25
Switchboard wattmeters	2.0
Recording instruments	2.0 –4.0
Energy (watt-hour meters)	
Continuous-current	2.5
Alternating-current, single-phase, no transformers	2.0
Alternating-current, single-phase with transformers	2.5
Alternating-current, polyphase with transformers	3.0
Frequency	
Portable instruments	0.5
Switchboard instruments	1.5
Power-factor	
Portable instruments (ammeter, voltmeter, wattmeter)	2.0
Switchboard instruments (above 90 per cent.)	1.0
Switchboard instruments (below 90 per cent.)	2.0 –4.0
Resistance	
Medium: 1.0 to 10,000 ohms with high-grade Wheatstone bridge	0.1
Less than 1 ohm or more than 10,000 ohms with high-grade Wheatstone bridge	0.2 –1.0
With portable bridges	0.5 –2.0
Low: By fall-of-potential method	0.5
With Thomson double bridge	0.05
High: (Insulation)	5.0
Conductivity	0.25
Magnetic measurements	2.5

6. Classes of errors. There are two general classes of errors in any kind of measurements, *a*, systematic and *b*, accidental. The former class affects each result in a series of similar observations in the same manner, as for example, an error in the standard used. The latter class includes those over which the observer has no control, such as observational errors in reading an indicating instrument. Accidental errors, unlike systematic errors, are as likely to be positive as negative and therefore tend to eliminate themselves

* Depends upon capacity and whether used with instrument transformers.

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from the mean value as the number of readings is increased. Where th necessary degree of reliability is not obtained in a single measurement, number of observations are made, from which the most probable true valu may be obtained, together with its probable error. These latter quantitie may be derived in different degrees of precision by various mathematic methods involving the theory of probabilities and the method of least square In all ordinary electrical measurements it will usually be sufficiently correc to assume that the true value is equal to the average of the various value obtained (eliminating systematic errors) plus or minus the average erro The average error is the average of the differences between the average valu and each individual value. It should be noted, however, that according t the theory of probability, the precision of the result does not increase directl but only as the square root of the number of observations made (see Par. 43 to 439).

7. **Certain general precautions** which should be observed in electric measurements, and certain sources of error which should be avoided, a indicated in the following paragraphs.

(a) **The probable limit of accuracy** of the standards, instrument and methods should be known.

(b) As a general proposition, in other than rough determinations, on measurement should not be relied upon. **Several readings** should b taken, and the conditions should be altered, wherever possible, in order t avoid accidental errors.

(c) Indicating instruments should be of such a range that the quantit under measurement will produce **a reasonably large deflection** on the scal The percentage observational error decreases in direct proportion as th magnitude of the deflection increases.

(d) The possible presence of **external or stray magnetic fields,** bot direct and alternating, should always be borne in mind. Such fields may b produced by current in neighboring conductors, or by various classes electrical machinery and apparatus, structural iron and steel in buildings, et These fields introduce errors by combining with the fields of portable ind cating instruments, galvanometers and other instruments utilizing a magneti field, and, in the case of alternating fields, by inducing small e.m.fs. in th loops formed in bridges, potentiometers, etc.

(e) In measurements involving high resistances and galvanometer such as bridges and potentiometers, possible "leakage" or shunt circuit should be eliminated. This is done by providing a **"guard" circuit** th principle of which is to keep all points to which the current might flo improperly, at the same potential as the highest in the apparatus. Se further discussion under potentiometers (Par. 49 to 52).

(f) **Temperature changes** in various parts of bridge, potentiometer an similar circuits should be avoided because of thermo e.m.fs. produced the junction of dissimilar metals. Such effects are often produced if th observer's hand comes in contact with the metal parts of the galvanomet key, switches, etc.

(g) Instruments with covers made of glass and hard rubber should not b rubbed, especially with a dry dust cloth. The **induced electrostati charge** on the moving element is often sufficient to change the deflectio materially.

(h) At potentials of 500 volts and above, the electrostatic attractio between moving and fixed parts may become serious. This is prevented b keeping the two parts at the **same electrostatic potential.** When ground ing is permissible, this can be done by connecting the circuit to earth at th point where the instrument is connected, care being taken that the movin coil end of the instrument is on the ground side. In very high potential wor this electrostatic attraction becomes very troublesome, so that the instru ments must be connected in circuit at a grounded part of the line, or el be thoroughly insulated from ground and the moving element connected t the case or to an electrostatic shield around the instrument.

GALVANOMETERS AND DETECTORS

8. **Galvanometers** are used extensively in all classes of electrical mea urements. Strictly speaking, the term applies to many other instruments f measuring current, such as voltmeters and ammeters, but it is ordinaril understood to apply to those instruments which are used to measure ver small electrical quantities.

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9. Classes of galvanometers. There are two general classes: (1) **moving magnetic needle**; (2) **moving coil.** In the former class, a small and (usually) permanent magnet is suspended at the centre of a coil of wire through which flows the current to be measured, producing a deflection. In moving coil galvanometers, a coil of relatively fine wire is suspended at the centre of a permanent or electromagnetic field; the current to be measured flows through this coil, producing a deflection. Moving-magnet instruments are most prominently represented by the tangent galvanometer and the Kelvin galvanometer; moving-coil instruments by D'Arsonval and electrodynamometer type galvanometers.

10. Direct-current types of galvanometers are represented by the following: Tangent galvanometers, sine galvanometers, the Kelvin type, D'Arsonval type, ballistic type, differential galvanometers, electrodynamometers and electrometers. These are described briefly in the following paragraphs. The first two, though obsolete, are of great historical importance.

11. Tangent galvanometers. In this instrument the magnetic needle is suspended or pivoted above the centre of a circular scale, over which moves the pointer attached to the magnet. The coil carrying the current is in a plane perpendicular to that of the scale, so that the direction of the field which it produces is in the plane of the magnet, the earth's magnetic field being the directing force. The current is approximately $I = 5rH \tan \alpha / \pi n$ (amp.), where r = radius of coil in centimeters; H = horizontal component of earth's field in gausses; n = number of turns in coil; and α = angle of deflection.

12. The sine galvanometer is similar to the tangent galvanometer, the essential difference being that the coil is moved as the needle deflects, so that they are finally in the same plane and sin α replaces tan α in the formula.

13. Kelvin galvanometer (astatic type). In this instrument there are two magnetic needles or sets of needles, of slightly different strengths, at opposite ends of a light quartz rod and oppositely directed. Each is at the centre of a pair of coils through which flows the current to be measured, these pairs being oppositely wound so that the moment exerted on the two needles is in the same direction. Thus the moving system is almost, but not quite, astatic. The controlling force is the earth's field modified as desired by means of a movable permanent magnet. This galvanometer must be calibrated against a standard. It is one of the most sensitive types of galvanometers known, instruments with a current sensibility of the order of 1×10^{-12} amperes having been built and used in research work.

The **Broca galvanometer** is a modern form of the Kelvin galvanometer. The magnets are two steel wires suspended vertically close together and with consequent poles at the center, making a moving system which has very small inertia and is highly astatic.

14. Moving coil or D'Arsonval galvanometers consist of a coil of fine wire suspended between the poles of a permanent horse-shoe magnet. The coil is usually suspended by a phosphor-bronze or steel wire, or flat strip, which not only conducts the current to the coil but provides the controlling force. Current is conducted from the coil by a helix of fine wire at the bottom. The strength of the field in the region occupied by the coil is increased by mounting a soft iron core in the central space enclosed by the coil, the pole pieces being shaped to give a uniform field throughout the space in which the coil moves. While the D'Arsonval galvanometer cannot readily be used to make absolute measurements, but requires calibration, its many advantages have made this the most generally used type of galvanometer in the electrical laboratory. It is practically independent of the earth's field or other external fields; its period can be made short, which, with its dead-beat qualities, makes it a much faster instrument than other types; it is comparatively rugged, simple to use and one instrument can be employed for a wide range of work.

The **Einthoven string galvanometer** is of the moving-coil type, but the coil is a single wire suspended between the poles of a powerful electromagnet. Its deflection is measured with a microscope.

15. Ballistic galvanometers are used to measure quantity of electricity (coulombs); such, for example, as the discharge from a condenser or the induced charge in a secondary circuit. Ballistic galvanometers may be of the moving-magnet or the D'Arsonval type. In order that the instrument may be perfectly ballistic the quantity to be measured must be completely di-

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charged through it before the suspended system has moved appreciably **The period**, or time of vibration, must therefore be long compared with th time of discharge. This is accomplished by increasing the inertia of th moving system.

16. Deflection of ballistic galvanometers. The magnitude of th first deflection is a measure of the quantity discharged into the instrumen In an instrument in which there is no damping (Par. **26**) such as the moving magnet type, the quantity may be calculated directly from the constant of the instrument. Thus

$$Q = \frac{2Ht \sin (\frac{1}{2})\alpha}{\pi G} \qquad \text{(coulomb)}$$

or for small angles, 5 deg. or less,

$$Q = \frac{Ht \sin \alpha}{\pi G} \qquad \text{(coulomb)}$$

where Q = quantity of electricity in coulombs, H = field strength in gausse G = constant computed from the coils, t = period in seconds, α = angle deflection.

17. Ballistic galvanometer constant. In practice, ballistic galvan ometers are usually standardized and the formula becomes very simple $Q = kd$ where d = deflection and k = quantity per unit deflection or galva nometer constant. The constant is determined with a standard condense or mutual inductance. The deflection obtained upon suddenly dischargin a charged condenser through the galvanometer is $d = Q = CE$; and hence $k = CE/d$, where Q = quantity of electricity in coulombs, E = potential to whic the condenser had been charged in volts, and C = capacity of condenser i farads. When a mutual inductance is used, the deflection is $d = Q = MI/$ and $k = MI/dR$, where Q = quantity of electricity in coulombs, M = coefficien of mutual inductance in henrys, I = steady or Ohm's law value of current i primary of mutual inductance in amperes, and R = resistance of secondar circuit (including the mutual inductance) in ohms.

18. A differential galvanometer is one provided with two independen coils or sets of coils by means of which two currents may be compare simultaneously. This method provides a means of measuring a current wit out making the circuit common with that of the comparison standard. I D'Arsonval instruments, the two coils are wound side by side on the sam frame and are connected in opposition, so that when the two currents bein compared are adjusted for zero deflection, their ratio is usually unity. Th actual ratio can be determined experimentally.

19. Electrometers. In the electrometer, a piece of thin aluminium suspended by a metallic suspension over four quadrants of sheet metal whic are insulated from each other and from the frame or support. Opposi quadrants are connected to each other and the two sets are connected respe tively to the two sides of the circuit to be measured. If a charge from condenser is placed on the moving vane, one end will be repelled and th opposite end attracted, producing a deflection which will be a measure the potential applied to the stationary quadrants. This instrument is e tremely sensitive, and while it is one of the earliest types of electrical measu ing instruments it is still used extensively in research work, especially whe the available energy is extremely small, as in measurements of radia energy.

20. Galvanometers as detectors. The majority of galvanometers a used as detectors only, that is, in zero-deflection methods where the kind of scal or proportionality of deflections does not enter into the determination. I such cases a very short, straight scale is sufficient and space may be econ mized by placing the galvanometer on the wall above the table, with th scale directly underneath. The beam of light is properly directed b suitable prisms and mirrors.

21. Reflecting galvanometers may be read with a telescope and scal or with a lamp and scale. In the former, the scale is reflected from th plane mirror (attached to the moving system) to the telescope through whi movements are observed. In the latter, an image of a narrow beam of lig (issuing from a narrow slit in a vessel enclosing a lamp, or from a portion an incandescent lamp filament) is thrown on to the scale by the mirror. I

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order to get a sharp image, either the mirror is made concave (with a 1-m. focus if the scale is the usual distance of 1 m. away), or a lens is used. Fig. 1 shows the general arrangement.

21. Galvanometer scales. When readings are to be taken, care should be exercised that they are proportional to the angular deflections. On a straight scale the deflection in millimetres is

$$d = A \tan 2\alpha \qquad (3)$$

where A = distance from mirror to scale in millimetres and α = angle through which the moving coil turns. If the angle is small, d is proportional to α. The error becomes about 0.5 per cent. at $\alpha = 5$ deg. Obviously a curved scale will eliminate this error, and by properly adjusting the curvature the readings may be made proportional to the angle or to any desired function of the angle.

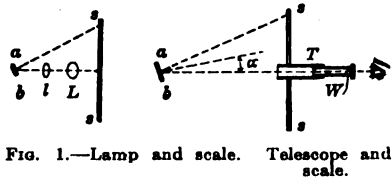


FIG. 1.—Lamp and scale. Telescope and scale.

22. The sensitivity of a galvanometer is expressed in one of several ways, the numerical expression of which is called the **galvanometer constant.** In instruments of the D'Arsonval type, the sensitivity depends upon the moment of inertia of the moving system, the torsional moment of the suspension, the field strength, and the number of turns and the area of the coil.

24. Different forms of galvanometer constants. The various constants are usually defined as follows:

(a) **The ampere constant** is the current in microamperes (millionths of an ampere) which will produce 1 mm. deflection on a scale 1 m. distant.

(b) **The megohm constant** is the number of megohms in series with the galvanometer through which one volt will produce 1 mm. deflection on a scale 1 m. distant.

(c) **The volt constant** is the potential in microvolts (millionths of a volt), across the galvanometer terminals which will produce a deflection of 1 mm. on a scale 1 m. distant. Or it may be expressed as the deflection in millimeters which will be produced by one microvolt.

(d) **The coulomb constant** refers to ballistic galvanometers (Par. 17) and is the quantity in microcoulombs (millionths of a coulomb) which will produce 1 mm. deflection on a scale 1 m. distant.

25. High current sensitivity is desirable for high-resistance measurements, such as insulation resistance. **High voltage sensitivity** is desirable for measurements involving small potentials, such as low-resistance bridges, potentiometers, etc. **High coulomb sensitivity** is desirable in magnetic tests.

26. Damping. This term is applied to those forces which collectively bring the moving system to rest after it has been set in motion. In order to shorten the period and facilitate readings, damping sometimes is intentionally produced mechanically with air vanes, or more generally by electrical means. The latter means include: (a) use of a metal frame on which the moving coil is wound and in which eddy currents are produced; (b) use of a closed loop of copper wire attached to the coil and in which eddy currents are produced; (c) use of the generator action of the swinging coil when its circuit is closed. The latter is the more convenient method for general purposes, because the damping can be readily changed by means of resistances in series or in parallel with the galvanometer.

27. Critical damping is that condition of damping where the moving system comes to zero position, or equilibrium, but does not pass through it, in the shortest time after deflection. A galvanometer is **aperiodic** when it is critically damped. It is **dead beat** when the coil deflects to its final position or reading without oscillation.

28. The period of a galvanometer is the time in seconds required for one complete oscillation, or the time between two successive passages through the zero or mid-position.

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29. Galvanometer shunts are combinations of resistances so arrange and so connected to the galvanometer that the constant of the latter may b quickly changed. Ordinary resistance boxes may be used as shunts for gal vanometers when the resistance of the galvanometer circuit is not too small

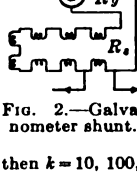


FIG. 2.—Galvanometer shunt.

In the latter case the box is connected as shown in Fig. 2 thus increasing the resistance R_g of the galvanometer cir cuit. The readings of the galvanometer must be multi plied by a factor

$$k = \frac{R_g + R_s}{R_s} \qquad (4$$

wherein R_g is the resistance of the galvanometer circui and R_s is that of the shunt. In special galvanomete shunts,

$$R_s = \frac{R_g}{9}, \frac{R_g}{99}, \frac{R_g}{999}, \frac{R_g}{9999}, \ldots\ldots \text{etc.} \qquad 5$$

then $k = 10$, 100, 1,000, 10,000 respectively.

30. The Ayrton or universal shunt is so arranged that it can be use with any galvanometer. When, in Fig. 3, the movable contact x is at b $I'_g = I r_{ab}/(r_{ab} + r_g)$, where I'_g = current through galvanometer, I = curren from battery, r_{ab} = resistance between a and b, and r_g = resistance of galva nometer. If the contact x is moved to c,

$$I''_g = I'_g\left(\frac{r_{ac}}{r_{ab}}\right) \qquad \text{(amp.)} \qquad (6$$

It will be noted that r_g is not in this equation; hence if the galvanomete constant is obtained with the shunt all in (x at b), the shunt ratio at any other position of x is r_{ac}/r_{ab} and is independent of the galvanometer resistance.

31. Alternating-current types of galvanometers include the following: Electrodynamometers, or, as they are more commonly known, dynamometers; vibration galvanometers, thermogalvanometers, electrostatic galvanometers, alternating-current detectors, barretters and bolometers.

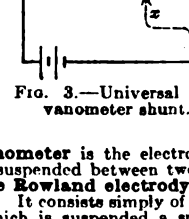


FIG. 3.—Universal galvanometer shunt.

32. Dynamometer-type instruments are used extensively in measurements of alternating currents because they measure mean effective values and can be calibrated on direct current. They can be used for a wide range of measurements of current, e.m.f. and power, from extremely small values to very large ones.

33. The operative principle of the dynamometer is the electrodynamic action between a movable coil (or coils) suspended between two or more fixed coils, all of which are energized. **The Rowland electrodynamometer*** is typical of this class of instruments. It consists simply of two fixed coils mounted close together, between which is suspended a small coil of very fine wire. Each fixed coil consists of two separate windings of different current capacities brought out to separate terminals. For e.m.f. measurements the moving coil and the fine wire fixed coils are connected in series; for current measurements, the moving coil is connected across a non-inductive shunt in the current circuit; for power measurements, the moving coil is connected across the circuit to be measured while the proper fixed coil is connected in series with it.

34. Dynamometers are made astatic, or independent of external fields, by having two sets of moving coils, oppositely wound, one above the other, with a common suspension. There may be one or more pairs of fixed coils. In heavy-current instruments, the fixed coils are wound with cable composed of many fine strands laid up in braided form. This reduces the eddy currents which otherwise would be set up and which would influence the moving coil.

* Rowland, H. A. "Electrical Measurements by Alternating Currents;" Leeds and Northrup Catalogue No. 74, 1911; p. 294.

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35. Vibration galvanometers* can be used only with alternating currents. There are two types, the **coil** and the **soft-iron magnet.** In the former, the moving element is a single wire or narrow coil of very fine wire suspended between the poles of a permanent magnet. An exceedingly small mirror is attached at the centre of the wire or coil. When the natural period of this moving system coincides with that of the current to be measured it will resonate and be sensitive to extremely small currents, the indication being the width of the spot of light on the screen or scale. The instrument is "tuned" or adjusted to resonance by changing the effective length of the suspension or its tension. The Einthoven galvanometer (Par. 14) makes a very sensitive vibration instrument.

In the soft-iron magnet type, a very small piece of soft iron is suspended by a silk fibre between the poles of a permanent horse-shoe magnet. Adjacent is a coil carrying the alternating current to be measured, which produces a field perpendicular to that of the permanent magnet. The temporarily magnetized needle vibrates in synchronism with the period of the alternating current and with an amplitude proportional to the strength of the current. The effective period of the moving system is adjusted to resonance, by shunting more or less of the permanent field by means of a movable keeper across the limbs of the magnet. Obviously these instruments can be used only for detector purposes, that is, in zero-method measurements, such as inductance and capacity measurements with a Wheatstone bridge.† They are extremely sensitive, being capable of detecting currents of the order of 1×10^{-8} amp. and are applicable to frequencies up to 1,000 cycles per sec.



FIG. 4.—Dudell thermo-galvanometer.

36. Thermo-galvanometers utilise the heating effect of an electric current and are independent of frequency. They can be constructed with practically no inductance or electrostatic capacity, and are therefore used extensively in high-frequency measurements. One of several forms is the Duddell type, Fig. 4, in which a moving coil, suspended between the poles of a permanent magnet as in D'Arsonval galvanometers, includes a bismuth-antimony thermocouple placed immediately near an electric heater through which passes the current to be measured. The instrument can be used for a wide range of measurements by changing the heater. It can be used on frequencies up to the order of 100,000 cycles per sec.

37. Electrostatic galvanometers utilise the force of repulsion between two bodies carrying electrostatic charges of the same polarity. One or more very thin metal vanes are suspended by a fine wire between two or more stationary vanes, so shaped (circular discs with opposite quadrants cut away) that when excited, the movable vanes swing outward from the fixed vanes between which they are interleaved. These instruments require no appreciable current and can be calibrated on direct current, thus possessing characteristics which make them valuable for measuring e.m.fs. where the current capacity is very small or nil.

38. Alternating-current detectors. Other methods of determining the condition of balance in zero-method alternating-current measurements are shown in Figs. 5 and 6. The former indicates the scheme of a **synchronous commutator.**‡ A commutator, C, and two slip-rings, r and r^1, are mounted on the shaft of a small synchronous motor. The bars in the commutator are narrow, and equal in number to the poles of the motor and equally spaced. Two brushes, a, a^1, connected to the galvanometer are so spaced as to bridge two bars simultaneously. These brushes are mounted on a disc which can be rotated about the shaft. The bars are connected alternately to the two

* Wenner, F. "Characteristics and Applications of Vibration Galvanometers;" *Trans.* A. I. E. E., 1912, Vol. XXXI, p. 1243

† Rosa, E. B. and Grover, F. W. "Measurement of Inductance by Anderson's Method Using Alternating Current and a Vibration Galvanometer;" Bureau of Standards Bulletin, Vol. I, 1905, p. 291.

‡ See also Frederick Bedell, "Use of Synchronous Commutators in Alternating-current Measurements;" *Jour. Franklin Institute*, Oct., 1913, p. 385.

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rings which in turn are connected through the brushes, b, b^1, to the alternati current being measured. It is apparent that the connections to the g vanometer are reversed every half cycle, so that the indication is a steady o the value of which may be made anything from zero to a maximum by sh ing the angular position of the brushes. Thus the most sensitive positi can be readily found, irrespective of the phase relation between the curr in the circuit being measured and the motor armature. The variation contact resistance at high speeds, and possible presence of thermo e.m. may cause trouble where the resistances or potentials are very low, as low-resistance bridge measurements.*

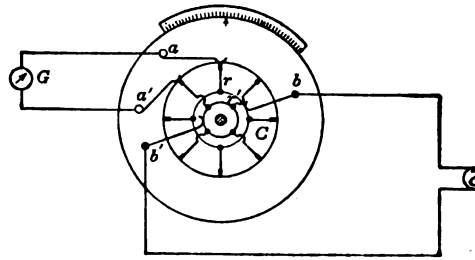


FIG. 5.—Synchronous commutator.

39. A synchronous reversing key which overcomes the latter difficul is indicated in Fig. 6. A cam, C, mounted on the shaft of a small synchrono motor is so designed that it moves the lever, l, up and down in such a mann that the pair of contacts, a and a^1, at the end of the lever make alternate co tact with the pairs of stationary contacts, c and c^1, once per cycle. The nu ber of projections on the cam of course will correspond with the number pairs of poles on the motor. The contacts are arranged as shown diagra matically at the right of Fig. 6, from which it will be seen that the connectio to the galvanometer are reversed every half cycle, so that a steady deflecti is obtained in the direct-current galvanometer. All the contacts are su

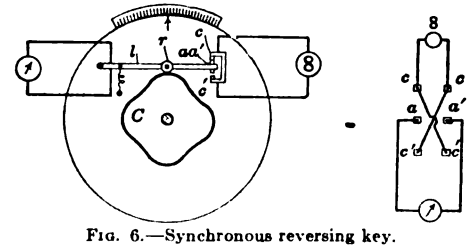


FIG. 6.—Synchronous reversing key.

ported on a solid disc which can be rotated around the shaft, and hence r versal can be made at any point on the wave as in the case of the synchronou commutator. The contacts are all made of platinum, the cam is hardene steel and the lever l is kept in contact with the cam at all times by means a spring. The roller r is necessary to insure contact at the low portion the cam.

* Sharp, C. H. and Crawford, W. W. "Some Recent Developments i Exact Alternating-current Measurements;" *Trans.* A. I. E. E., 1910, Vol XXIX, p. 1518.

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40. A barreter* is a bridge arrangement (Par. 143) in which the change in resistance with the passage of current of a high temperature coefficient wire is utilized to measure currents of telephone magnitude and frequency.

41. A bolometer is an instrument devised by Prof. S. P. Langley with which extremely small temperature changes (order of 0.0001 deg. fahr.) may be measured. A very thin strip of platinum or other metal is exposed to the radiation from a suitable source heated by the current to be measured. This strip forms the arm of a balanced Wheatstone bridge and the change in resistance corresponding to the change in temperature is indicated by the galvanometer deflection.

CONTINUOUS-E.M.F. MEASUREMENTS

42. Standards of e.m.f. The legal unit of e.m.f. in the United States is the **international volt** adopted by Act of Congress in 1894; in practice the prefix is generally omitted. This unit is the e.m.f. which, when applied to a conductor having a resistance of one international ohm, will produce a current of one international ampere. The Act also states that the volt "is represented sufficiently well for practical use by 1000/1434ths of the e.m.f. between the poles or electrodes of the voltaic cell known as Clark's cell at a temperature of 15 deg. cent. and prepared in the manner described in the accompanying specification." The Clark cell has since been superseded by the Weston cell as the standard of e.m.f. The value of the latter as adopted by the Bureau of Standards, Jan. 1, 1911 is 1.0183 at 20 deg. cent., which is now the standard of e.m.f. in this country.

43. The Clark cell was the first form of voltaic cell to meet the requirements of a reliable standard of e.m.f., namely, reproducibility and reasonable permanence. The elements are: positive electrode, metallic mercury; negative electrode, amalgamated zinc; electrolyte, saturated solution of zinc sulphate and mercurous sulphate. Its e.m.f. in terms of fundamental or c.g.s. units was originally taken as 1.434 international volts at 15 deg. cent., the value having been made legal in 1894 as stated above. Later and more careful determinations have shown, however, that 1.4328 is a more correct figure. The e.m.f. of the Clark cell changes with temperature in accordance with the formula:

$$E = 1.4328[1 - 0.00077(t^\circ \text{ C.} - 15)] \qquad (7)$$

where E = international volts at any temperature, t deg. cent.

44. Objections to Clark cell. As the electrical art developed and more precise working standards became necessary, the defects in the Clark cell were noted. The most conspicuous of these are large temperature coefficient, large temperature lag and difficulty in obtaining the temperature. This cell has therefore been superseded by the Weston cells, which are practically free from these objections.

45. Weston cells.† There are two forms of Weston cells, the **saturated** cell and the **unsaturated cell.** The elements are: positive electrode, metallic mercury; negative electrode, amalgamated cadmium; electrolyte, solution of cadmium sulphate and mercurous sulphate.

46. Weston normal cell. In this cell the electrolyte is saturated. This form is the official standard because it is more permanent and can be reproduced with greater accuracy than when the electrolyte is unsaturated. When carefully made according to the official specifications, cells will agree with each other within a few parts in 100,000. The e.m.f. changes slightly with temperature according to the following formula:

$$E = 1.0183[1 - 0.000041(t^\circ \text{ C.} - 20)] \qquad (8)$$

where E = international volts at any temperature, t deg. cent.

47. The unsaturated Weston cell, on the other hand, has practically no temperature coefficient (0.00001 per deg. cent.). Although it is not so reliable as a fundamental standard as the Weston normal cell, and each cell has to be standardized, it is, nevertheless, more convenient for general use. This is the form furnished by the Weston Electrical Instrument Co. The makers recommend that these cells be not subjected to temperatures below

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*Cohen and Shepard, "Telephone Transmission Measurements," *Jour. Inst. E. E.*, 1907, Vol. XXXIV, p. 503.

†See Circular No. 29, Bureau of Standards, 1910.

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4 deg. cent. or above 40 deg. cent., and that no current greater than 0.000 amp. be passed through them.

48. Comparisons of continuous electromotive forces with a standard cell. Electromotive forces may be compared with a standard cell by several methods. The more typical methods are based on the following principles.

(a) In the **substitution method**, the current flowing through a high resistance (not less than 15,000 ohms) is measured with a high-sensibility galvanometer, first with the standard cell in the circuit and then with the unknown e.m.f. substituted for the standard cell. The resistance being the same in the two cases, the deflections are proportional to the e.m.fs. $E = ed'/d$, where E = unknown e.m.f., e = standard cell e.m.f., d = deflection with standard cell and d' = deflection with unknown e.m.f.

(b) The **equal deflection method** is a modification of the above, in which the deflections are kept the same in the two cases by changing the resistance. Then $E = er'/r$, where r = total resistance of the circuit, including the galvanometer, with the standard cell in the circuit and r' = total resistance with the unknown e.m.f. This method is better than (a) because it is a constant deflection method and the result depends on the known values of two resistances, rather than observed deflections.

(c) In **Wheatstone's modification** of the equal deflection method, the galvanometer resistance does not have to be known. The deflection, d, is noted when the unknown e.m.f., E, and a known high resistance are in circuit. Additional resistance, r', is added and the deflection, d', again noted. Similarly with the standard cell of potential difference, e; the resistance is adjusted until the same deflection, d, is obtained and then an amount of resistance, r, is added until the deflection d' is again obtained. The unknown e.m.f. is $E = er'/r$.

(d) In the **condenser discharge method** a condenser is charged, first from the unknown e.m.f., then from the standard cell, and discharged in each instance through a ballistic galvanometer. The deflections will be proportional to the e.m.fs., hence $E = ed'/d$ as in (a). Obviously, if the unknown e.m.f. is much smaller or much larger than the standard cell, the deflection can be made about equal to that of the standard cell by using a larger or a smaller condenser. In that case the ratio of the capacities should be known, and then $E = ed'C'/dC$, where C = capacity of condenser used with the unknown e.m.f. and C' = capacity of condenser used with the standard cell. This method has the advantage that practically no current is required, which is advantageous in making measurements of voltaic cells of very small capacity or rapid polarization.

(e) The principle of the **opposition or potentiometer method** is that of opposing the e.m.f. of the standard cell against an equal difference of potential which bears a known proportion to the unknown e.m.f. This method is the most accurate and by far the most generally used, because it is both a zero-deflection and a zero-current method, the result depending only on the ratio of two resistances which can be very accurately determined. Potentiometers are instruments employing this principle (Par. 49).

49. Description of Leeds and Northrup potentiometer, low resistance type. Fig. 7 shows the arrangements of the circuits. The figures for the second decimal place and beyond are obtained from a slide wire at the end of the circuit, CB, along which a contact moves. A special dial is also provided for the standard cell (at the left) and separate contacts are provided for the standard-cell e.m.f. and the unknown e.m.f., so that no settings have to be disturbed when checking the secondary current in the potentiometer circuit. The essential part of the instrument consists of 15 five-ohm coils AC, connected in series with the extended wire, CB, the resistance of which from 0 to 1,100 scale divisions is 5.5 ohms. Thus when the current from the battery, B, is adjusted by the rheostat, R, to 0.02 amp., the fall of potential across each 5-ohm coil in AC is 0.1 volt and across CB, 0.11 volt. Since the latter is divided into 1,100 parts, the e.m.f. may be measured to 0.000 volt. At point 5 in AC, a wire is permanently attached connecting to one point of the double switch, U. When this switch is thrown to the left, the standard cell is connected through the galvanometer to point 5 and the sliding contact T which moves over the dial at the left consisting of 19 resistance coils. Between a and A is a resistance which is adjusted to such a value that with 0.02 amp. flowing, the potential drop between 5 and a is

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1.0175 with 0.0001 volt additional drop across each dial coil, giving a maximum of 1.0194. This range will include the usual differences between different Weston standard cells. To adjust the current to 0.02 amp., throw the switch U to the position indicated by the dotted lines, set the contact T to correspond to the e.m.f. of the standard cell and regulate R until the galvanometer shows no deflection. The unknown e.m.f. is then measured by throwing the switch U to the position indicated by the full lines and adjusting the contacts M and M' until no deflection is noted. After a balance has been obtained, the current may be checked by simply shifting U to the first position and pressing the contact key.

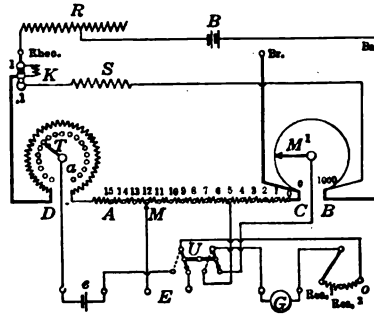


FIG. 7.—Leeds & Northrup potentiometer.

50. Paul potentiometer, low resistance type. Fig. 8 is the connection diagram. It is similar to the instrument described in Par. 49 in that the lower part of the reading is obtained from an extended slide-wire on one end, and a standard-cell switch is provided at the other end. The rheostats for adjusting the battery current are within the instrument (R and r). The slide wire is laid straight, with divisions equal to about ¼ in. (0.4 cm.), which correspond to 0.001 volt divided into 5 subdivisions. A special switch, S, is so arranged that the various circuits 1, 2, 3, etc., may be quickly connected to the potentiometer circuit. The resistance of the standard type is 10 ohms per volt, with a range from 0.0002 volt to 1.8 volt. It is also made with ranges as low as 0.000004 volt to 0.036 volt for thermoelectric work.

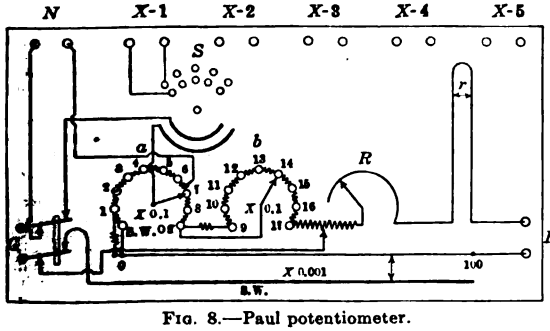


FIG. 8.—Paul potentiometer.

51. Wolff potentiometer, high resistance type. Fig. 9 shows the diagram of connections in the latest model. The total resistance is 20,000 ohms and there is no slide wire, all resistances being comprised in the form of 5 dials, having steps of 1,000, 100, 10, 1 and 0.1 ohm respectively. These read 0.1, 0.01, 0.001, 0.0001 and 0.00001 volt respectively. Instead of obtaining a balance by moving along the main circuit the contacts connected to "X," as in the slide wire form, the final balance is obtained by adding or subtracting resistance in the main circuit between these two contacts; the

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three low dials are so arranged that a corresponding change is automatically made in the external part of the main circuit and the total resistance is kep constant. A separate dial is provided for the standard-cell adjustment together with a separate resistance which can be altered to accommodat different cells without affecting the measuring circuits. The total range o the instrument is 1.9 volts.

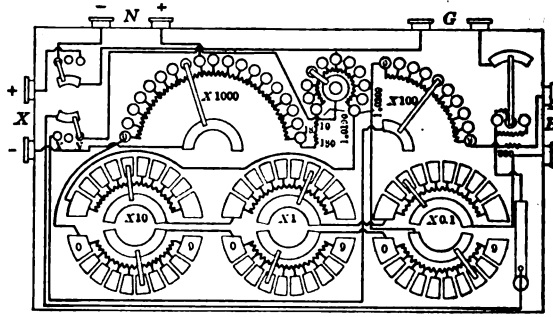


FIG. 9.—Wolff potentiometer.

52. Care and use of potentiometers. The following notes apply t the use of potentiometers in ordinary work.

(a) The accessories should be suitable for the particular type of in strument, that is, high or low resistance, and for the class of measuremen to be made. The galvanometer should be sufficiently sensitive to give a pe ceptible deflection when there is an unbalance equal to the smallest scal division in the potentiometer curcuit. A low-resistance galvanometer, o the order of 100 ohms, should be used with a low-resistance potentiometer and a high-resistance galvanometer of 500 to 1,000 or more ohms, with high-resistance potentiometer. Similarly, the resistance of the volt bo (Par. **53**) for low-resistance potentiometers should be as low as the permi sible power loss in the resistance coils will permit. This is usually abou 5,000 ohms for 150 volts. For high-resistance instruments, the resistance 1,000 ohms or more per volt.

(b) The **first trials for balance** should always be made with a resistanc in series with the galvanometer. This is usually provided in the instrumen with facilities for readily cutting it out of circuit when an accurate balance being obtained. The resistance protects the galvanometer and also th standard cell from the effects of excessive currents.

(c) Trouble is sometimes experienced, especially in damp weather, due t **current "leaking to ground"** from the potentiometer circuits in a mann which produces a false deflection. This can be obviated by providing **"guard circuit."** In one scheme of this kind all of the apparatus is place on small, hard-rubber pillars each of which in turn rests on a small met plate. These are connected together and to the positive "*x*" binding-po by fine bare wire. Thus all points to which current might "leak" over th surface are kept at the highest external potential to which the potentiomet is connected. When the surfaces become noticeably moist, conditions ca be improved by carefully wiping with a cloth moistened with grain alcoho

(d) **Calibration and checking.** The essential requirement is that th ratio of the resistance of each step to that resistance between the standar cell terminals shall be the same as the ratio of the corresponding potential For example, if the standard cell e.m.f. is 1.0183 volts and the resistanc between its terminals is 101.83 ohms, the resistance of the various ste should be adjusted to 10 ohms per 0.1 volt. If the standard cell resistanc is 102.848 ohms the potentiometer is still accurate if the resistance throughou the circuit is adjusted to 10.1 ohms per 0.1 volt.

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53. Volt boxes. When the potential to be measured is greater than the range of the potentiometer (usually 1.5 volts) a volt box is used. It consists of a number of resistance coils connected in series, with taps brought out to binding posts. Fig. 10 shows the diagrammatic arrangement, in two forms. In (*A*), the potentiometer is connected to the posts marked "+" and "−." When the potential to be measured is between 1.5 and 15 volts, it is connected to the "+" and "15" posts, between which the resistance is just ten times that between "+" and "−." Hence only one-tenth of the unknown potential is applied to the potentiometer, the readings of which must therefore be multiplied by 10. Similarly, when the potential is between 15 and 150 volts, it is connected to the "+" and "150" posts, and the ratio becomes 100. In (*B*), Fig. 10, the potential to be measured is always connected to one pair of posts, designated "+" and "−," and the potentiometer connections are shifted to obtain the desired ratio. Theoretically the former method is the better because the resistance in parallel with the potentiometer is constant and the sensibility is therefore constant. In the latter case, the sensibility varies, being a minimum with the lowest ratio, or when the maximum amount of resistance is in parallel with the potentiometer. On the

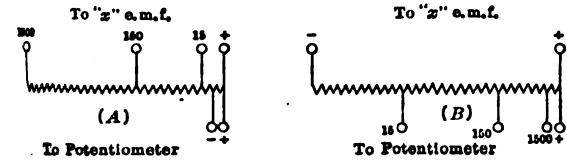


FIG. 10.—Volt boxes.

other hand, the unknown e.m.f. is always connected to a high resistance, and hence there is no danger of burning out the volt box; this occasionally happens with the first form, (*A*), due to accidental connection with the wrong terminals.

54. Deflection potentiometers. Precision measurements obviously can be made only with very steady sources of e.m.f. If the e.m.f. is not steady, and a higher precision than that obtainable with secondary standards (voltmeters) is desired, a deflection potentiometer may be employed. In this instrument the greater part of the e.m.f. is measured by balancing against the potentiometer current in the regular manner, and the remainder is obtained from the indication of the calibrated galvanometer, which is preferably of the portable type. The **Brooks deflection potentiometer*** is of this type.

55. Voltmeters for continuous e.m.fs. Indicating instruments called voltmeters are used in ordinary commercial measurements. They are, essentially, low-sensibility galvanometers provided with scales over which moves a pointer attached to the moving system. The scale is calibrated in volts by comparison with an indicating instrument of higher sensibility, or by means of a potentiometer. Practically all direct-current voltmeters employ the principle of **D'Arsonval galvanometers** as shown in Fig. 11. They consist essentially of a light rectangular coil of fine copper wire wound upon an aluminium frame, pivoted in jeweled bearings and capable of rotating in the annular space between the soft-iron core and the pole-pieces of the permanent magnet. The aluminium frame, being a closed secondary circuit, acts as a brake or damper when the coil is deflected; the instrument is thus made "dead beat." The pole-pieces are so shaped that the magnetic field strength is uniform throughout the space in which the coil moves. The field strength varies widely in different makes of instrument, ranging from 500 to 3,000 lines per square centimeter in the air gap and 1,000 to 6,000

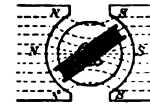


FIG. 11.—Diagram, Weston d.c. voltmeter.

* Bureau of Standards Bulletin; Vol. II, p. 225; Vol. IV, p. 275; Vol. VIII, pp. 395 and 419.

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lines per square centimeter in the steel. A light tubular pointer attache to the coil moves over a calibrated scale. The current is introduce into the coil by two spiral springs which also provide the controllin force. Since the field strength and the gradient of the controlling force are uniform, the deflection is strictly proportional to the current passin through the coil, and the scale divisions are uniform. A large amount resistance is connected in series with the moving coil in order to make th current small. Thus the same instrument can be made suitable for a wid range of voltages by changing the amount of series resistance. This r sistance is made of wire having a low temperature coefficient in order neutralize as much as possible the effect of the large coefficient of the copp in the coil.

56. Voltmeter characteristics (continuous current). The usu **resistance** of portable voltmeters of this type varies from 50 to 150 ohm per volt and the **current sensibility** from 7 to 20 milliamperes at full-sca deflection. The resistance of the moving coils is about 75 ohms. Th **torque** varies from 2 to 6 millimeter-grams at maximum current, with **ratio of torque to weight** (in grams) of 1 to 5. The **temperatur coefficient** is usually negligible, being of the order of 0.01 to 0.02 per cen per deg. cent. at full scale.

57. Laboratory standard voltmeters (continuous current). Sc called laboratory standard voltmeters are similar to portable instrumen except that they are larger, have a longer pointer, a longer and more ope scale and are made with greater care. They are only semi-portable and a intended primarily for standardizing purposes.

58. Switchboard voltmeters (continuous current) are usually of th D'Arsonval type. The construction is the same as that of portable instru ments, except that they are more substantial and rugged, especially r regards the moving system, in order to withstand the harder conditions c continuous service and excessive fluctuations. They are mounted in iro cases to protect them as much as possible from the normal stray fields du to the bus bars.

59. Effect of stray fields. The general effect of stray fields on the stand ard types of portable and switchboard instruments is shown in the table i Par. **60.** These errors are usually only temporary and disappear with th stray field. When the field is very strong, as under short-circuit condition in a neighboring conductor, **demagnetization** of the instrument magnet may result in a permanent error. Shields are likely to be of little value unde such conditions because the iron becomes saturated.

60. Effect of Stray Magnetic Fields on Continuous-current Volt meters and Millivoltmeters

Stray field, lines per sq. cm.*	Error at two-thirds full-scale deflection, per cent	
	Shielded	Unshielded
5	0.5 to 1.0	2
10	0.75 to 1.75	3.5 to 5.5
15	1.0 to 3.0	6.0 to 7.5
20	1.25 to 3.25	7.5 to 10

61. The measurement of very small continuous potentials may b effected by some of the methods outlined in Par. **48.**

A potentiometer is most convenient, high resistance for high resistance source such as small galvanic cells and low resistance for low resistance sources such a thermocouples.

62. Ground detectors. Those of the direct-current type are usuall special forms of voltmeters. In one form, there are two coils, differentiall wound on the moving system. One end of each coil is connected to groun and the two free ends are connected respectively to the two sides of th

* The field produced at a distance of 30 cm. (12 in.) from a conductor carry ing 3,000 amp. is about 20 lines per square centimeter.

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system. When there is no ground or fault on the system, the pointer stands at the centre of the scale, in normal equilibrium. When a ground or fault occurs, current flows through the coil connected to the ungrounded side, producing a deflection. In another form of detector a standard voltmeter, without the series resistance, is connected to the centre of a resistance shunted across the line, with the remaining terminal connected to ground.

ALTERNATING-E.M.F. MEASUREMENTS

63. Measurements of alternating e.m.f. In alternating e. m. fs. there are three values to be considered; the maximum, the average and the "root-mean-square" or mean effective value (Sec. 2). The last value is the one usually required, being the value of the equivalent continuous e.m.f. Since the standard of e.m.f. is the standard cell, the measurement of alternating potentials involves, like continuous potentials, comparison with the standard cell. The comparison may be more or less a direct one, as in precision measurements, or it may be indirect by means of secondary standards which in turn have been standardized by direct comparison.

64. Precision measurements of alternating e.m.f. Obviously an alternating e.m.f. cannot be compared directly with the standard cell, the e.m.f. of which is unidirectional and constant. The comparison is made therefore by a substitution or "transfer" method. A galvanometer of the electrodynamometer type, or an electrostatic galvanometer, is connected to the alternating potential to be measured and the deflection noted. It is then connected to an adjustable continuous potential which is manipulated until exactly the same deflection is obtained. The continuous potential is then compared with the standard cell by means of a potentiometer, in the usual manner. A double-throw double-pole switch is usually arranged so that the transfer from alternating current to continuous current can be quickly made, without allowing the deflection to change appreciably, the continuous potential having been previously adjusted to about the proper value. Two readings, direct and reversed, are taken on continuous current at the same reading as the alternating deflection; the average of these two is taken as the true value, thus eliminating the effect of stray magnetic or electrostatic fields. It is obvious that, on account of this indirect method, alternating-e.m.f. measurements cannot be made with the degree of precision obtainable in measurements of continuous e.m.fs.

65. Secondary standards. The dynamometer type instruments which are used as secondary standards of alternating current are adapted to e.m.f. measurements by constructing the windings of a large number of turns of fine wires, instead of a few turns of heavy wires. See Par. **99**.

66. Classification of alternating-current voltmeters. The voltmeters in general use may be divided into five types, as follows: dynamometer, soft-iron vane, induction, hot-wire and electrostatic.

67. Dynamometer type voltmeters (alternating current) depend upon the reaction between a fixed and a moving coil connected in series. The



FIG. 12.—Diagram, Weston dynamometer type a.c. voltmeter.

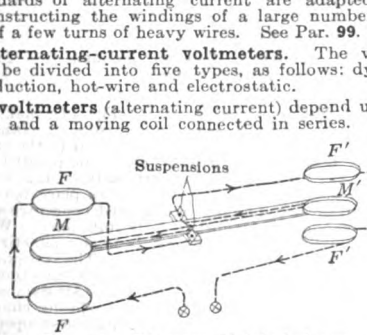


FIG. 13.—Diagram, Kelvin balance.

movement of the movable coil is a measure of the current flowing through the coils and therefore proportional to the e.m.f. impressed at the terminals. In one form (**Weston** model 18), a single coil moves within two parallel fixed

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coils as shown in Fig. 12, where F, F' are the fixed coils and M is the movi coil, to which a pointer P is attached. The deflection is approximately pr portional to the square of the current. The scale is compressed at the upp end instead of extended because the coil moves beyond the uniform part of t field. The **Thomson Inclined Coil voltmeter** is similar, except that t plane of the fixed coils makes an angle of about 45 deg. with the shaft of t moving coil for the purpose of making the scale more uniform.

In the **Westinghouse** type Q, the **Kelvin balance** principle is use This principle is shown in Fig. 13, where there are two coils, MM', attach to opposite ends of a beam which is supported at the middle and free to mo Each coil moves between a pair of fixed coils, F F and F' F', and all of t coils are connected in series in such a manner that the moments of all t forces on the movable system, taken about the beam axis, are cumulati thus tending to produce rotation. In the Kelvin balance the controllin or opposing force is a weight moved along a graduated scale attached the beam supporting the movable coils; the moment of this weight abo the beam axis, when the moving system is balanced, varies as the squa of the e.m.f. In the Westinghouse instrument the coils are arranged v tically and the controlling force is a spiral spring. The amount of co pression of this spring necessary to balance the electromagnetic forces, indicated by a pointer moving over a scale, is a measure of the e.m.f. Sing coil instruments are direct reading and hence fluctuating e.m.fs. can be mo easily read on them than on the torsionhead instruments, but the latter a astatic and therefore practically independent of stray fields.

68. Soft-iron-vane voltmeters (alternating current) utilise the action between a temporarily magnetised piece of soft iron and the magnet ing field. In the **Thomson inclined coil instrument** of this type t

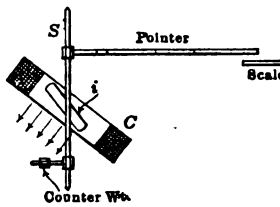


FIG. 14.—Diagram, Thomson inclined coil a.c. voltmeter.

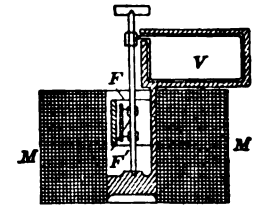


FIG. 15.—Diagram, West soft-iron type a.c. voltmete

plane of the energising coil, C (Fig. 14), makes an angle with the shaft, which carries a member, i, comprising a rectangular piece of very thin, s iron. This piece of iron is so attached to the shaft that rotation is produc by the tendency of the iron to become parallel with the field established the coil. In **Weston instruments** of this type (model 155), the reacti which produces the deflection takes place between two pieces of soft ir bent in the arc of a circle and placed concentrically, one of which, F' (Fig. 1 is movable, and the other, F, is stationary. When the surrounding coil, is energized, the pieces of iron become magnetised in like manner, so that t resulting force is one of repulsion. The stationary piece F is made triangu in shape, with the pointed end in the direction of rotation, for the purp of making the scale more uniform. Air damping is obtained by means o light aluminium vane, V, in an enclosing chamber, C. This type has great advantages of low price, ruggedness, open scale and small weight.

69. Induction-type voltmeters (alternating current) utilise the pr ciple of induction watt-hour meters (Par. **202**), or the rotative tendency o free cup of thin metal when placed within a so-called revolving magne field. Actual rotation of the movable element is prevented by an opposi spiral spring, so that the deflections become a measure of the current in t energising coils. The **Westinghouse** type P voltmeter is an import

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example of this type, for which is claimed a very high ratio of torque to weight of moving element, rugged and simple construction, extremely long scale and compactness.* The arrangement of the circuits is shown in Fig. 16. The primary winding, *P*, which is connected to the line circuit, induces a current in the secondary winding, *S*, opposite in phase to the primary current. The secondary current passes through two auxiliary coils, *AA'*, wound in opposite directions on the poles. The field produced by these coils will be displaced 90 deg. in time phase from the field produced by the primary winding and approximately at right angles thereto in space, thus producing the necessary rotating field to cause the cup, *C*, to tend to rotate. Incidentally, the inherent frequency error of induction type instruments is largely neutralized by this combined transformer and induction motor action, the effect of frequency changes being opposite in the two cases.

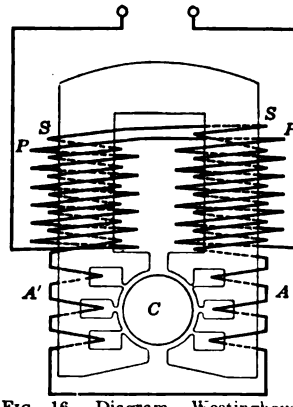


FIG. 16.—Diagram, Westinghouse induction-type a.c. voltmeter.

70. Hot-wire voltmeters† (alternating-current) utilize the expansion and contraction of a wire carrying a current proportional to the e.m.f. to be measured. Fig. 17 shows the principal features of the **Hartmann and Braun voltmeter**. The current flows through the platinum-iridium alloy wire, *AB*, which expands under the heat produced. This expansion reduces the tension on the fine phosphor-bronze wire, *CF*, which in turn allows the silk fibre, *HE*, attached to the spring, *S*, to be pulled to the left. This fibre passes around a small pulley on the shaft of the moving system and thus produces a deflection of the pointer. Damping is effected by the aluminium disc, *D*, moving between the poles of the permanent magnet, *M*. The hot wire, *AB*, is in series with a large non-inductive resistance, *R*, so that the current is proportional to the e.m.f.

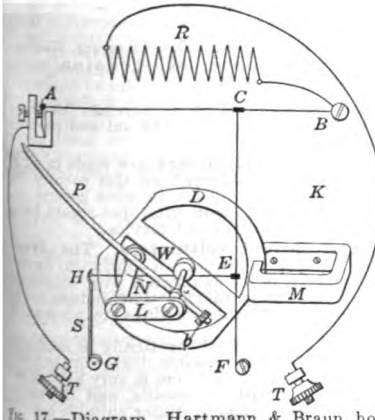


FIG. 17.—Diagram, Hartmann & Braun hot-wire type a.c. voltmeter.

71. Electrostatic voltmeters (alternating-current) are similar to electrostatic galvanometers (Par. **37**) or electrometers, except that they are designed for measuring larger potentials and are provided

*MacGahan, P. "Induction Type Indicating Instruments;" *Trans.* A. I. E. E., 1912; Vol. XXXI, p. 1565.

†Pierce, A. W. and Tressler, M. E. "Hot-wire Instruments;" *Trans.* A. I. E. E., 1912; Vol. XXXI, p. 1591.

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with scales which make them direct reading. They are made in a great variet of forms, for both portable and switchboard use, but are used commercially much more in Europe than in this country. The principle of their operation i shown in Fig. 18, in which mm' is a thin aluminium vane suspended or pivote between two pairs of fixed vanes, ff'. The deflection through moderate range is proportional to the square of the potential and is controlled either by a spir spring or by gravity. Damping is produced magnetically, by air vanes, o by immersing the elements in oil. For ordinary commercial voltages a num ber of sets of vanes are arranged one above the other in a vertical positio and connected in parallel, thus multiplying the effect (Fig. 19). For high voltages, one set of vanes is sufficient and they are usually placed in a vertic plane with the moving element mounted on a horizontal shaft. In th **Westinghouse electrostatic voltmeter**, the moving system is not co nected to the circuit; Fig. 20 shows the arrangement of the parts. Whe potential is applied to A and A', the hollow cylinders C and C' become opp sitely charged by induction. The resultant attraction produces a deflectio because of the shape of the fixed plates, P and P'. The condensers K an K' are each formed by two flat plates and are connected in series with and A' to increase the range. For lower ranges these condensers are shor circuited, so that ranges of 30,000, 60,000 and 100,000 volts are available i the same instrument and on one scale. The elements are entirely immerse

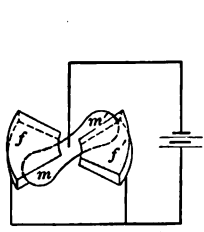


FIG. 18.—Diagram, electrostatic-type a.c. voltmeter.

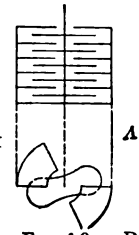


FIG. 19.—Diagram, electrostatic-type a.c. voltmeter.

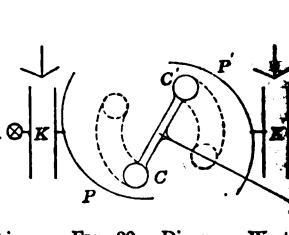


FIG. 20.—Diagram, Westing house high-tension volt meter.

in oil which permits a relatively compact construction, increases the torqu because of the greater specific inductive capacity of the oil and provide damping.

72. Alternating-current switchboard voltmeters are made in all the types described above (Par. **66** to **70**), although in this country th dynamometer, soft-iron vane and induction types are in most general us They are similar in general to the portable instruments, due regard bein given to the more severe requirements of switchboard service.

73. Calibration of alternating-current voltmeters. The dyna mometer type of voltmeter gives the same indication on continuous curren as on alternating current and may therefore be calibrated with continuou currents, direct and reversed readings being taken. The inductance i instruments of commercial ranges is so small that the readings are independen of standard frequencies.

The soft-iron-vane type of voltmeter should theoretically be used onl on alternating current because hysteresis occurs to some degree in the vane Practically, however, the hysteresis is so small that there is very little differ ence between the respective indications with increasing and decreasin potential. Provided with a steady source of e.m.f., under suitable contro these instruments may be calibrated with continuous current by taking th average of the "up" and "down" potential readings corresponding to th various points. Care should be taken that the potential is increased o decreased only to the desired value and not beyond it. Theoretically, in struments of the soft-iron type are not independent of frequency or wave form; practically, however, the variation is not measurable throughou commercial ranges.

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Hot-wire voltmeters are theoretically and practically independent of changes in frequency and wave form, and can therefore be calibrated with continuous current. They are especially suitable for high-frequency measurements.

Induction-type voltmeters are affected by changes of frequency. They must therefore be calibrated on alternating current of the frequency for which they have been adjusted, in comparison with some secondary standard which can in turn be calibrated with continuous current as described under precision measurements. Errors which result from ordinary variations in commercial wave forms are negligible.

Electrostatic voltmeters are independent of changes both in frequency and in wave form, and may therefore be calibrated with continuous current where the range will permit.

74. **The effect of stray fields on alternating-current voltmeters** is very marked in some types of instruments. The error will vary with the deflection and with the direction of the superposed field. In the case of unshielded, single-coil dynamometer instruments, the error caused by a magnetic stray field of five lines per square centimeter may vary from 25 per cent. at quarter scale to 5 per cent. or 10 per cent. at three-quarters scale; with a field of 10 lines per square centimeter these figures may become 75 per cent. and 25 per cent., respectively. Soft-iron-vane instruments are much less affected, a stray field of 10 lines per square centimeter causing about 10 per cent. error. Hot-wire and electrostatic instruments are not affected. Shielded dynamometer instruments are available in which the error with stray fields of 20 lines per square centimeter is only 1 or 2 per cent.

75. **Measurement of small alternating e.m.fs.** The single-coil dynamometer type voltmeter is practically the only one available for potentials of less than 25 volts. Since the deflections in this type of instrument are proportional to the square of the potential, the lowest value that can be measured with a 7.5-volt instrument is about 2.5 to 3 volts. By separately exciting the fixed coils the sensibility will be greatly increased, because the deflections will then be directly proportional to the potential impressed on the moving coil. The **"unipivot" dynamometer type** instrument (Paul) with separate binding posts for fixed and moving coils is intended to be used in this manner, full scale deflection being obtained with 1 volt.

For the accurate measurement of potentials of the order of 0.25 volt and less, dynamometer instruments must be of the suspension, reflecting type. Care should be taken that the excitation is in phase with the potential being measured and that the current through the instrument remains proportional to the potential. This current is $I = E/\sqrt{R^2 + L^2\omega^2}$, wherein E = impressed voltage being measured, R = resistance of instrument, L = inductance and $\omega = 2\pi \times$ frequency. When R is large the inductance is negligible, but when it becomes small as in very low reading instruments, it may have to be considered in the measurement. In that case, the instrument can be calibrated as an ammeter on continuous current and the alternating e.m.f. computed with the above formula. For similar reasons, the temperature coefficient may become significant.

76. **Measurement of large alternating e.m.fs.** Theoretically, any alternating potential can be measured with any of the voltmeters described, if sufficient series resistance is used. In a practical sense, the large energy consumption and the insulation difficulties limit their use to measurements of a few thousand volts, and then only for testing purposes. In connection with commercial generation and transmission, potentials up to about 33,000 volts are almost universally measured in this country by means of step-down instrument transformers (shunt type) connected to ordinary voltmeters.

The measurement of potentials higher than 33,000 volts is usually required only in connection with high-voltage tests. The various methods of making such measurements are as follows:

(a) **Ratio of the step-up power transformer,** in connection with an ordinary voltmeter on the low tension side. This method requires an accurate knowledge of the transformer ratio under various conditions of load and potential, information which is often difficult to obtain.

(b) **Step-down instrument transformers** (shunt type) with an ordinary voltmeter. This method requires an accurate knowledge of the transformer ratio at various potentials, with the voltmeter as the secondary

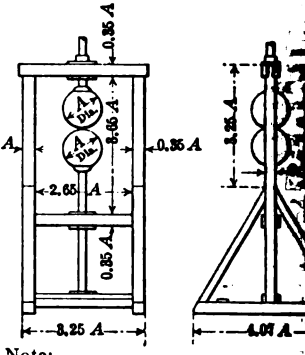
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load. The method is simple, convenient and accurate, but the power c sumption and the cost of the transformer become prohibitive at h potentials.

(c) **Electrostatic voltmeter.** Commercial instruments are availa up to about 200,000 volts. They require no appreciable power and are q satisfactory. The principal objections are the high cost of large sizes and lack of dead-beat qualities.

(d) **Test coil.** Where the source of the high potential to be measu is a testing transformer, an ordinary low-reading voltmeter can be connec to a few turns of the high tension winding brought out to separate termin These turns should be at the grounded end of the winding. The ra under all conditions, will be that of these turns to the total turns in the hi tension winding, if the transformer has been well designed. This metho generally sufficiently accurate and is very convenient.

(e) **Spark gaps.** The sparking distance between two terminals atmospheric air is a standard method of measuring high potentials. T maximum length of gap which a given potential will break down deper in this case, on the maximum value and not upon the virtual or effect value which is the value obtained in the other methods. The maxim value, however, is the important one in tests of insulators and insulat materials. When the wave form is not a sine curve the maximum value may deviate materially from the theoretical value, which is the virtual (voltmeter reading) value multiplied by $\sqrt{2}$.



Note;
A Variation of 1 Cm. in Thickness an Width of Wood Parts is Permissible

FIG. 21.—Sphere spark gap.

77. Needle-point and sphere spark gaps. The needle-point gap was for many years the standard method of measuring high voltages, but it is unsatisfactory for very high potentials because of variations due to atmospheric pressure, humidity, proximity of surrounding objects and sharpness of the needle-points. Spheres are now used instead of needle points for the higher values.* A gap with carefully machined and polished spheres gives very reliable and consistent results due, probably, to the fact that the gap breaks down before corona forms and perhaps also to the lesser dielectric spark lag.† The A. I. E. E. Standardization Rules (Sec. 24) recommend the use of the sphere gap for voltages above 50 kv. and preferably do to 30 kv. The needle gap may however be used from 10 kv. to 50 kv.

78. A. I. E. E. standard sparking distances in air, with needl point and sphere gaps are given in Sec. 24.

79. Ratio of shunt-type instrument transformer. When a ve accurate measurement (within 2 per cent.) of a high potential is to made with an instrument transformer of the shunt type, the nominal ra cannot be relied upon as being sufficiently correct and the true ratio shou be determined by a direct measurement. In the accurate measurement power and energy the phase angle should also be known (Par. 179). F the accurate determination of the ratio of instrument transformers of t shunt type, the following methods are typical.

(a) **Direct measurement** of the primary and the secondary volta

* Farnsworth, S. W. and Fortescue, C. L. "The Sphere Spark Gap *Proc.* A. I. E. E., 1913, Vol XXXII, No. 2, p. 301. See Fig. 21.

† Minton, J. P. "Effect of Dielectric Spark Lag on Spark Gaps," *Gene Electric Review* (1913), Vol. XVI, p. 514.

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preferably with two similar voltmeters. Fig. 22 shows diagrammatically the connections for this method. The voltmeters V_1 and V_2 are similar, and the resistance R is adjusted until the two deflections are about alike. The two voltmeters are then connected in parallel on the secondary of the transformer and the indication of V_2, corresponding to the previous indication of V_1, is noted. The ratio is given by:

$$\left(\frac{R+r_v}{r_v}\right)\frac{X_1}{X_2} \qquad (9)$$

wherein R = resistance in series with V_2; r_v = resistance of voltmeter V_2; X_1 = first reading of V_2; X_2 = second reading of V_2.

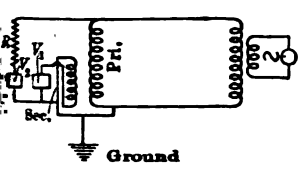


FIG. 22.—Connections—ratio of shunt type transformers.

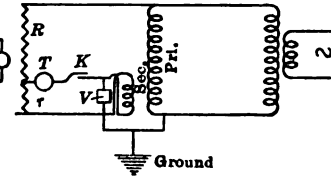
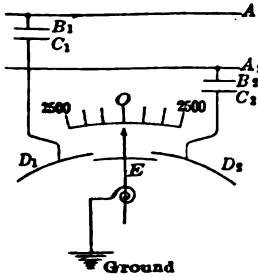


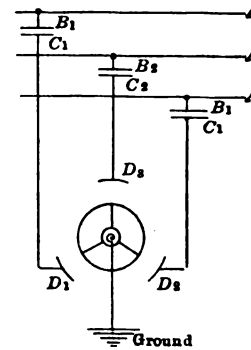
FIG. 23.—Connections—ratio of shunt type transformers.

(b) **Opposition method.** The secondary voltage is reversed and connected in opposition to a part of the primary voltage, the ratio being measured in terms of two resistances. Fig. 23 shows the scheme. The resistance r is varied until the detector, T, indicates zero or a minimum deflection. The desired ratio is evidently expressed by $(R+r)/r$.

The detector may be either a telephone receiver, a dynamometer instrument, or a synchronous reversing key with direct-current galvanometers (Par. 39). The telephone receiver is not sensitive at commercial frequencies,



Single Phase Detector



Three Phase Detector

FIG. 24.—Diagram, Westinghouse a.c. ground detector.

and if harmonics are present the precise balance point for the fundamental frequency is difficult to locate. When using a dynamometer, the fixed coils are connected in series with R (not r) and the moving coil in place of T. When a rectifier is used, it is connected directly in place of T.

(c) **Comparison with standard transformer.** H. B. Brooks* proposes

*Brooks, H. B. *Electrical World*, Nov. 1, 1913, p. 898.

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a simple and convenient method of comparing two transformers by mea of a wattmeter.

80. Alternating-current ground detectors are usually **electr static** instruments. Fig. 24 shows diagrammatically the principle of **We inghouse detectors.** The stationary vanes are connected through cc densers to the main lines, and the movable vane is connected to grou In the single-phase detector, a charge will be induced on each end of the mc able vane, opposite in sign to that on the corresponding stationary va setting up forces of attraction. When the system is free from groun these attractive forces are equal and opposed to each other; hence the mc ing system stands at zero. A ground on either phase wire produces an u balanced condition and a deflection away from the grounded conductor. the three-phase detector, the vanes are sectors of spheres, the movable va being mounted on a universal bearing.

81. General Electric ground detectors operate on a principle simi to that last described. Four quadrants, or fixed, flat vanes are cross-cc nected and mounted between them is a moving vane connected to grou Opposite sets of fixed vanes are connected to the two sides of the line circ and the action is the same as described in Par. **80.** The **three-pha detector** is similar, consisting of three pairs of fixed quadrants mount 120 deg. apart on a common base plate, and a flat moving vane with th corresponding sectors.

CONTINUOUS-CURRENT MEASUREMENTS

82. Absolute measurements of current. The fundamental unit current, as derived from the centimeter, gram and second, is defined terms of the dimensions of the conductor and the strength of the magne field produced by the current. Absolute measurements of current are the fore made with instruments so carefully constructed that the current c be calculated from their dimensions.

83. Instruments for absolute measurement of current. Absolu determinations have usually been made with two classes of instruments. the first, the deflection of a magnetic needle at the centre of a coil is measur and the current is calculated from the dimensions of the coil, the strength the earth's field and the torsion of the suspension. The best known exam of this class is the tangent galvanometer (Par. **11**). This method involv of course, any error in the determination of the earth's field. In the otl class of instruments, the needle is replaced with a suspended coil. When t length and the radius of both movable and fixed coils are in the ratio $\sqrt{3} : 1$, when the centres coincide and when the dimensions of the fixed c are large compared with those of the movable coil, it has been shown Gray that the torque exerted by the moving system is expressed by

$$T = \frac{4\pi^2 N n r^2 I}{\sqrt{D^2+L^2}} \quad \text{(dyne-cm.)} \qquad (1$$

where N = number of turns in fixed coil, n = number of turns in movable cc D = diameter of fixed coil in centimeters, L = length of fixed coil in centimete r = radius of movable coil in centimeters, and I = current (coils in serie Hence by measuring the torque (weighing it), the current can be determin directly in C.G.S. units.

84. Practical unit and standard of current. It would be qu impracticable to make ordinary measurements in terms of the fundamen unit, by the methods indicated above (Par. **82** and **83**). The Act of Congr of 1894 which legalized certain practical units of electrical measure defin the practical unit of current, or the **international ampere**, as one-ten of the fundamental C.G.S. unit. This Act also defined the standard u of current as the rate of deposition of silver at the cathode of a silver vo ameter (Par. **86**) constructed and operated under certain prescribed con tions, the ampere being the current which will deposit 0.001118 g. silver per sec. in a standard voltameter.

85. Methods of measuring continuous currents. The seve methods of measuring continuous currents may be classified as follov voltameter; potentiometer; and ammeters.

86. Voltameter method of current measurement. When a cc tinuous current is passed through an electrolyte, the latter is decomposed

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a rate which is proportional to the current strength, and an apparatus for measuring current by such means is called a voltameter. In the **silver voltameter**, the cathode or negative electrode is always platinum, the anode or positive electrode is pure silver, and the electrolyte is silver nitrate. Fig. 25 shows the general form. The anode is usually a silver rod projecting into a platinum bowl, which rests in turn on a copper plate. In cheaper forms, plates of silver and platinum are supported in a glass jar. The solution is usually about 15 per cent. (by weight) silver nitrate, and the effective area of the anode is about 50 sq. cm. per ampere. In order to prevent disintegrated silver on the anode from dropping on the cathode, the anode is surrounded with pure filter paper or a porous cup made of unglazed porcelain; in other cases, merely a shallow glass dish is placed beneath the anode. Recent investigations at the Bureau of Standards* have shown, however, that the chemical activity of filter paper results in an excessive deposit of silver and that the porous cup is much more suitable. The average current in amperes is computed from the formula

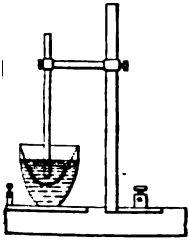


FIG. 25.—Silver voltameter.

$$I = \frac{M}{0.001118\,t} \quad \text{(amp.)} \qquad (11)$$

where M = weight of silver deposited in grams, t = total time in seconds and 0.001118 = electrochemical equivalent of silver (Sec. 19).

87. The copper voltameter is used to measure very large currents. The anode is electrolytically pure copper, the cathode is either copper or platinum, and the electrolyte is a solution of pure copper sulphate in the proportion of 10 g. of crystals to 40 cu. cm. distilled water. Two anodes may be used in order to utilize both sides of the cathode (Fig. 26) and the current capacity may be further increased by connecting additional plates in parallel. The current density should not exceed 1 amp. per square centimeter of cathode area.

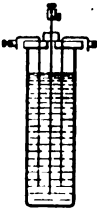


FIG. 26.—Copper voltameter.

88. In the gas or water voltameter the electrodes are two plates made of platinum, and the electrolyte is a 10 per cent. solution of sulphuric acid. In the electrolysis of this solution, hydrogen gas is formed at the cathode and oxygen gas at the anode. The total gas formed collects above the liquid, and is measured volumetrically in a closed graduated tube forming the upper part of the containing vessel.

89. Potentiometer method of measuring continuous currents. Although the silver voltameter is the legal standard for the measurement of current, its use is practically limited to reference measurements or primary standardization. It is seldom used in commercial measurements because it is much more convenient to measure current in terms of the volt and the ohm. Even in measurements of the highest precision, current is determined from the fall of potential across a standard resistance (Par. **113**), the potential being measured with a potentiometer (Par. **48** (a), **49**, **50**, **51**). The potentiometer method is not only more convenient than the voltameter method, but it is much more rapid and at least equal in accuracy, because it depends only on the measurements of a difference of potential and a resistance, both of which can be determined with a very high degree of precision.

90. Indicating continuous-current instruments which indicate current directly by the deflection of a pointer over a marked scale are called ammeters. Modern continuous-current ammeters are almost universally simple millivoltmeters of the D'Arsonval type connected to the terminals of a resistance (shunt) which in turn is connected in series with the main circuit whose current is to be measured. The deflections of the instrument will be proportional to the fall of potential across the shunt, and therefore to the current flowing through it. A millivoltmeter may be made an ammeter of any capacity by simply changing the resistance of the shunt.

*Bureau of Standards Bulletin, Vol. IX (1912), No. 2.

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91. D'Arsonval type of continuous-current ammeter. The pr ciple of these instruments has been described under "e.m.f. measurement (Par. 55). They are usually designed to have a full scale deflection with to 200 millivolts (thousandths of a volt) at the terminals. The resistance the moving coil is much lower (0.5 to 5.0 ohms) than that of voltmeters, order to make the millivolt constant high.

92. Continuous-current ammeters of the switchboard type intended for continuous operation and the shunt loss should therefore be lo They are designed for 50 to 75 millivolts at full scale deflection. High-gra portable ammeters are designed for 100 to 200 millivolts at full scale defl tion, in order to permit the use of resistance in series with the moving c thus reducing the temperature error, which is more important than the lar shunt loss.

93. Shunts for continuous-current ammeters. In switchbo ammeters and the lower grade portable ammeters of 25-amp. ratings a less, the shunt is within the instrument case. Above 25-amp. ratings, t shunt is usually separate from the instrument and means of connection provided by special flexible leads, which are included in circuit when t instrument is calibrated, since they form a part of the resistance of the ent instrument circuit. Obviously, these leads should never be alter without recalibrating the instrument. In high-grade ammeters the shun are separate for all capacities.

94. Construction of ammeter shunts. Ammeter shunts are constructed as to have a resistance which will be constant, as nearly possible, under all conditions. The resistance metal has a low temperatu coefficient, and the temperature is kept low either by connecting seve strips in parallel and making the current density low, or by making the c rent density high and using short lengths of the resistance metal with hea copper terminals designed to dissipate the heat by conduction and radiatio The former method is most generally used, the strips being silver-solder into relatively heavy copper or brass terminals which are connected into t circuit to be measured. The resistance metal should also have a low therm e.m.f. (Sec. 2) in junctions with copper.

95. Reduction of temperature errors in continuous-curre ammeters. Because of the large temperature coefficient of copper, it very undesirable to connect the moving coil of the instrument directly to the shunt. Temperature errors are reduced to a negligible value by connecting sufficient resistance having a low temperature coefficient (manganin or similar metal) directly in series with the moving coil as shown in Fig. 27, or by arranging a compensating circuit as shown in Fig. 28, where C = moving coil, R_m = low-coefficient resistance wire, and R_c = copper resistance wire.

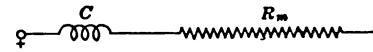


FIG. 27.—Temperature compensation in millivoltmeters.

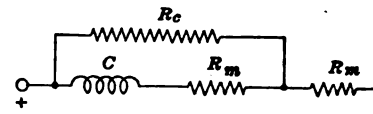


FIG. 28.—Temperature compensation in millivoltmeters.

96. The calibration of D'Arsonval type ammeters is effected adjustment of the resistance of the shunt, the resistance of the millivo meter circuit, or both. Formerly each instrument and shunt were adjus together, but it is becoming customary to adjust all of the instruments a given type to deflect full scale with the same potential in millivolts at t terminals. The shunts for these instruments are all similarly adjusted give the same potential drop, thus making all shunts and instruments o given type interchangeable. The shunts should be adjusted by varyi the main-line resistance between the potential taps and not by adjusti resistance wire connected in series with the instrument leads. In calibrati switchboard instruments and the lower grade portable instruments, t potential terminals are attached to the main current terminals and adju

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ment is effected by reducing the cross-section of the resistance strips which has been purposely left too large. In instruments of higher grade, the potential terminals are connected to the resistance strips inside the main terminals; approximate adjustment is obtained by trial, and after soldering the tap wire to the resistance strip, final adjustment is obtained by varying the cross-section, or by cutting back a tongue-shaped piece of the strip whose end is soldered to the tap wire.

ALTERNATING-CURRENT MEASUREMENTS

97. Measurements of alternating currents. There are, in the case of alternating currents, three values to consider, the maximum, the average and the mean effective or root-mean-square; the last is the value usually desired. Alternating currents, like alternating e.m.fs., can only be compared with the standard by means of a "transfer" instrument, that is, one in which the effect produced by a current is the same whether the current is continuous or alternating. Having determined the indication produced by the alternating current to be measured, the value of a continuous current which will produce the same deflection is obtained in terms of the standard.

98. Precision measurements of alternating current are made with "transfer" instruments (Par. **64**) which are usually of the reflecting, suspension, electrodynamometer class. The principle of these instruments is described in Par. **32** to **34**. P. G. Agnew has developed a tubular water-cooled electrodynamometer having a capacity of 5,000 amperes and an accuracy of 0.05 per cent. *

99. Secondary standards for alternating-current measurements, adapted for direct observation, must obviously be capable of calibration on continuous current. There are several instruments which fulfil this requirement.

The **Siemens electrodynamometer** consists of two stationary coils connected in series, with a moving coil suspended between them by a silk fibre. The deflecting force or moment is opposed by a spiral spring, which is twisted by hand (in the so-called **torsion head**) until the moving coil is brought back to the zero position. The amount of this twist, as indicated on a scale over which moves a pointer attached to the torsion head, is a measure of the current. The final relation of the fixed and moving coils is therefore always the same. The current in amperes is $I = k\sqrt{L}$, where L = twist of torsion head in degrees and k = a constant determined by calibration on continuous current. The instrument is sensitive to stray fields, from both direct and alternating current. The presence of such fields can be detected by passing current through the moving coil only; a deflection under such conditions indicates a stray field. Its effect may be reduced to a negligible quantity by turning the whole instrument until no deflection is noted.

100. The Kelvin balance (Par. **67**) is an electrodynamometer type of instrument which is astatic and in which the forces of attraction and repulsion are actually weighed as in an ordinary balance. Kelvin current balances are troublesome to use unless the current is extremely steady, a condition which rarely exists with alternating currents; they have therefore been practically superseded, in this country at least, by other and more reliable, convenient instruments of the dynamometer type, of which the Westinghouse "precision" ammeter is an example.

The **Westinghouse "precision" ammeter** is practically a Kelvin balance, of relatively small dimensions, in a vertical instead of a horizontal plane. The electromagnetic forces are opposed by a helical spring which is twisted by means of a torsion head as in the Siemens dynamometer. The angular movement of the torsion head necessary to keep the moving system in the zero position is a measure of the current. The actual value of the current is equal to the square root of the deflection, multiplied by a constant.

101. Types of alternating-current ammeters. The four principal types of commercial ammeters are as follows: dynamometer, soft-iron vane, induction, and hot wire. They are similar to the voltmeters of the same types (Par. **67** to **70**), except that the windings consist of relatively few turns of

* Agnew, P. G. "A Tubular Electrodynamometer for Heavy Currents." Reprint No. 184, Bureau of Standards, June 17, 1912.

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coarse wire instead of a large number of turns of fine wire, the ampere-tu being about the same in both cases. Hot-wire ammeters with ratings more than 1 or 2 amp. are usually small current instruments connected non-inductive shunts, as already described in principle (Par. **90**).

102. Measurements of large alternating currents. The only ty of ammeter which is generally used in the direct measurement of la alternating currents is the hot-wire ammeter, because it can be used w shunts. While shunts are made for capacities of 1,000 amp. and over, accuracy with shunts of very large capacity depends upon the care tal in the design to eliminate the eddy-current and skin-effect errors. The m common method is to use current transformers of the series type, to st down the current to a small value, usually 5 amp., which is convenient measure with standard instruments.

103. Series-type instrument transformers (also known as curr transformers) serve two purposes; the convenient measurement of large c rents, and the insulation of instruments and apparatus from high-volt circuits. They are similar to so-called power transformers, except that latter are connected in shunt across the line and the secondary potent remains substantially constant irrespective of the connected load. Se transformers are connected in series with the primary line, and the second current remains substantially constant for a wide range of loads. The lo consists of instruments or other devices which are connected directly in se with the secondary winding.

104. Measurement of ratio of series transformers. The ra of series-type instrument transformers may be determined by measuring primary and secondary currents directly with current-measuring instrume but obviously such a method is much less accurate than null or "zero" methods. The principle of the latter is the same as that of the potentiometer. A non-inductive resistance in the secondary circuit is adjusted until the potential drop across it is equal to that in a non-inductive resistance in the primary circuit. The ratio of the two resistances is equal to the ratio of transformation. The differences among the various null methods are largely in the manner of determining the balance and in measuring the phase angle. Fig. 29 shows the scheme of a method used at the Bureau of Standards,* where a reflecting dynamometer is used as the detecting instrument. R^1 and R^2 are the resistances in the primary and secondary circuits, respectively. The fixed coil of a dynamometer, D_1, is connected in series with the primary; then, with the switch S thrown to the right, R_2 is adjusted until zero deflection is obtain The component of the potential drop in R_2, which is in phase with that R_1, is thus equal in magnitude to the drop in R'. Since the phase angle always very small, the ratio of R_2 to R_1 may be taken as the transform ratio. The phase angle is then determined by measuring the component the R_2 drop which is 90 deg. from the R_1 drop, by means of another dyn mometer, D_2, the fixed coils of which are excited by a current displaced deg. in phase from the primary current.

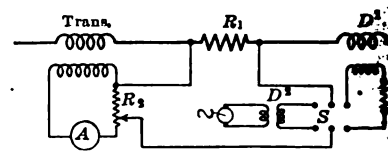


FIG. 29.—Connections for measuring ratio o series type transformers.

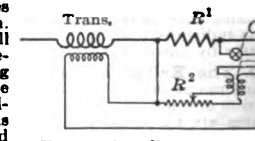


FIG. 30.—Connections measuring ratio of series ty transformers.

Fig. 30 shows the scheme of a method used at the Electrical Testi Laboratories.† R_1 and R_2 are the primary and secondary resistanc

* Bureau of Standards Bulletin, Vol. VII, 1913, No. 3, p. 423.

† Sharp, C. H. and Crawford, W. W., *Trans.* A. I. E. E., 1910, Vol. XXI p. 1517.

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respectively, and *C* is the detector which in this case is a synchronously driven reversing key (Par. **38**) connected to a Paul "unipivot" galvanometer. The secondary of a mutual inductance, *M*, is in the detector circuit and the primary of the inductance is in series with the secondary circuit of the transformer. After the value of R_2 has been found which will make the "in-phase" potential drops balance each other, the quadrature drop in R_2 is balanced by the e.m.f. in the secondary of the variable mutual inductance. Knowing the value of this inductance, the value of the phase angle may be calculated.

106. Ratio of series-type instrument transformers. Theoretically, the ratio of transformation should be the same as the ratio of the secondary turns to the primary turns, and the secondary current should be in exact phase opposition to the primary current. Actually neither of these conditions exists because of the current required to excite the core and supply the losses.

In many commercial measurements these errors can be neglected, but in accurate measurements of current, power and energy, the true ratio should be known. In power and energy measurements, the phase angle (angle between the actual vector position of the secondary current and the theoretical position which is 180 deg. from the primary current) should also be known. See Par. **179.**

106. Measurements of small alternating currents. The methods described for measuring small alternating e.m.fs. (Par. **75**) may be used for similar measurements of current. Portable ammeters of the soft-iron-vane type are made with ratings as low as 50 or 75 milliamperes at full scale; the impedance of such instruments is much higher than that of dynamometer instruments. The dynamometer type, when separately excited, can be used to measure currents as low as 10 milliamperes, with fair accuracy; one form made by Paul has a maximum range of 20 milliamperes. For very small currents, reflecting dynamometers are the most suitable.

107. Measurements of high-frequency alternating currents. High-frequency currents are best measured by methods involving the heating effect of the current. In the Fleming thermoelectric ammeter for relatively large currents the high-frequency current flows through a number of very fine copper wires stretched between the two terminals. These wires are separated in space and each carries about 2.5 amp., additional wires being added up

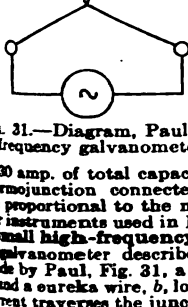


FIG. 31.—Diagram, Paul high-frequency galvanometer.

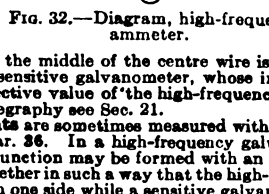


FIG. 32.—Diagram, high-frequency ammeter.

to 30 amp. of total capacity. At the middle of the centre wire is placed a thermojunction connected to a sensitive galvanometer, whose indications are proportional to the mean effective value of the high-frequency current. For instruments used in Radiotelegraphy see Sec. 21.

Small high-frequency currents are sometimes measured with the thermogalvanometer described in Par. **36**. In a high-frequency galvanometer made by Paul, Fig. 31, a thermojunction may be formed with an iron wire, *a*, and a eureka wire, *b*, looped together in such a way that the high-frequency current traverses the junction from one side while a sensitive galvanometer is connected to the other. Similar instruments in which the measured current does not flow through the joint are stated to be superior because of the absence of the Peltier effect* (Sec. 2).

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*Douse, C. M. *The Electrician*, London; Aug. 19, 1910; p. 765.

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Another practical method of measuring small high-frequency currents indicated in Fig. 32, where a and a' are two fine wires of different materia stretched between two terminals. The wires leading to the galvanomet are of the same materials, but so connected that a' and b are alike, and a ar b' are alike. Thus there are two therm couples in series. Obviously the connectio should be at the same potential, and this adjusted on continuous current with dire and reversed readings. In a bridge metho the current is measured by the change in r sistance of a carbon lamp (with a very sm filament) in one arm of a bridge, Fig. 33; i ductance coils, a and a' prevent the hig frequency current from flowing through t bridge.

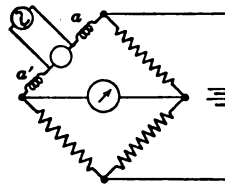


FIG. 33.—High frequency current measurements—bridge method.

108. Measurement of rectifier current. Either of two values of the current from rectifier may be required, the average valu or the root-mean-square value. In conne tion with storage-battery charging, the avera value corresponds to the equivalent c.c. val and a permanent-magnet type of measuring instrument should be use On the other hand, the power taken by incandescent lamps varies as t square of the current, and the equivalent c.c. current should be measur with instruments which indicate the mean effective value such as hot-wire dynamometer ammeters.

109. Measurements of telephone currents. Telephone currents m be measured with a form of potentiometer* or with a barretter (Par. 40) b since telephone currents are of constantly varying amplitude and frequenc measurements made by this and the above methods are usually of little valu Telephonic intensities are usually compared by ear with a telephone, usi artificial standardized cables. Where quantitative measurements are r quired, a high-sensibility oscillograph can be used.†

RESISTANCE MEASUREMENTS

110. Resistance standards in general. The practical unit of resis ance, the **ohm**, is represented by a column of mercury having certain dime sions (Sec. 1). This standard is obviously difficult to construct, maints and use; and, in general, will be found only in the laboratories of t national custodians of the fundamental electrical standards.

Secondary standards are therefore employed in actual measuremen These are made with metal of high specific resistance, in the form of wire, ribbon. Manganin (a copper-nickel-manganese alloy) is most u because, when properly treated and aged, it meets the necessary requireme These requirements are: permanent electrical and physical characteristi low thermo e.m.f. in junctions with copper; small temperature coefficien resistance; and relatively high specific resistance. The completed stand must, in addition, be unaffected by immersion in oil, or by changes atmospheric conditions.

111. Classes of resistance standards. In general, resistance stand may be divided into two classes: standards of resistance, or those u primarily for the measurement of resistance; and current standards, those intended primarily for the measurement of current.

112. General construction of standards of resistance. Stand of resistance have very small current capacity. They are made in two for the **Reichsanstalt** and the **N.B.S.** (National Bureau of Standards).‡ former is shown, partially in section, in Fig. 34. The N.B.S. form is sho Fig. 35. The distinctive features of the latter form are that it is imm in oil and hermetically sealed. This prevents the absorption of moistu

* Drysdale, C. V. "Alternating-current Potentiometer for Measu Telephone Currents," *London Electrician*, Aug. 1, 1913.

† Gati, B. Report of Second International Conference, European T phone and Telegraph Administrations; 1910.

‡ Bureau of Standards Bulletin, Vol. V, 1908, p. 413.

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the shellac and the consequent expansion of the fine wire used in the larger resistances.* Both forms are intended to be hung from mercury cups by means of lugs, and suspended in an oil bath in order to measure the temperature more accurately. The N.B.S. form is made only in sizes larger than 1 ohm.

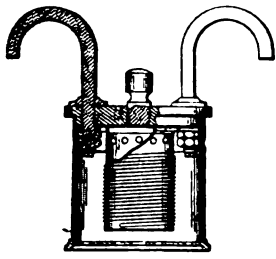


FIG. 34.—Standard resistance—Reichsanstalt form.

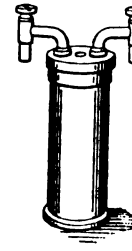


FIG. 35.—Standard resistance—N.B.S. form.

113. Current standards are made in two forms, the **Reichsanstalt** and **air-cooled.** The Reichsanstalt standards are made in two types, the small pattern for moderate currents, and the large pattern (in low resistances) for large currents. The small-pattern form is similar in appearance to Fig. 34 except that for 1 ohm and less, separate potential taps are provided. They are suspended from mercury cups in an oil bath for cooling purposes. The current ratings assigned by Otto Wolff and the Leeds and Northrup Company to small-pattern, Reichsanstalt form of standards are as follows: When used for resistance measurements 0.3 and 1.0 watt, for still-air-cooling and oil-cooling respectively. When used for current measurements with a temperature rise of 10 deg. cent., 2.5 and 10 watts for still-air-cooling and oil-cooling respectively. Large-pattern low-resistance current standards have capacities from 100 watts to 2,500 watts and over.

114. Air-cooled current standards employ sufficient material to permit of use in air without excessive temperature rise. While they are not as accurate or as reliable as the Reichsanstalt form, they are amply satisfactory for much commercial work, especially where oil baths would be inconvenient. Fig. 36 shows a Leeds and Northrup Co. resistance, of 0.0002 ohm, and 2,000 amp. capacity, for which an accuracy of 0.04 per cent. is claimed.

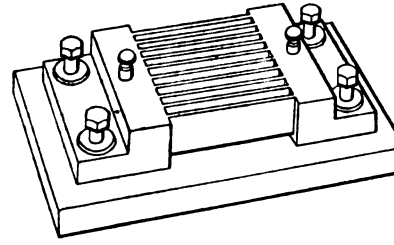


FIG. 36.—Leeds & Northrup air-cooled standard resistance.

115. Measurements of conductor resistance. There is no sharp distinction between materials commonly called conductors and those called insulators. Resistances of the former class may, however, be relatively high or relatively low, and certain methods of measurement are especially applicable to each class.

116. The fall-of-potential method consists simply in noting the voltage with a known current flowing through the resistance, and calculating the resistance from Ohm's law, $R = E/I$. This method is not suitable for

*Bureau of Standards Bulletin, Vol. IV, 1907, p. 121.

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very high or very low resistances and the accuracy depends upon the measure ment of two unknown quantities with indicating instruments. Furthermor the current required to give a readable drop may cause overheating. Th method should therefore be used with caution and only where accuracy i subordinate to simplicity and convenience. The potential should b measured, when possible, between points well within the current connec tions, especially when the resistance is low and the current is high. Greate accura y can be obtained by substituting a standard resistance in place o the ammeter, and noting the drop across it, and across the unknown resist ance, in succession. The latter is then equal to the ratio of the two reading multiplied by the standard resistance. The accuracy will be greatest whe the two resistances are nearly equal.

117. Bridge methods are the most accurate for resistance measurement because: (a) they are zero methods; (b) comparison is made directly witl standardised resistances, the accuracy of which can be made very high. Th principal types of bridges are known as Wheatstone, slide-wire, Carey Foster and Kelvin.

118. Wheatstone bridge. The Wheatstone bridge is most generall used for the measurement of all but the highest and the lowest resistance Fig. 37 shows the theoretical arrangement of a Wheatstone bridge whe r, r_1, and r_2 are accurately known resist- ances and r_x is the resistance to be meas- ured. When using the bridge, the various resistances are adjusted until the galva- nometer, G, shows no current flowing;

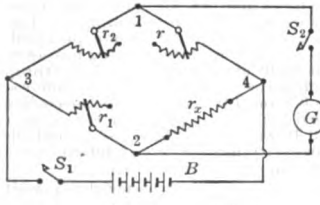


FIG. 37.—Diagram of Wheatstone bridge.

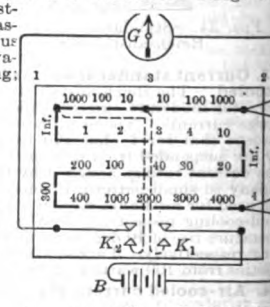


FIG. 38.—Wheatstone bridge—Postoffice form.

then, $r_x = (r_1/r_2)r$. The battery switch, S_1, should always be closed befor the galvanometer switch, S_2, in order to protect the galvanometer from th momentary rush of current. The galvanometer and the battery may b interchanged without affecting the result (Sec. 2, Par. **30**).

119. Forms of Wheatstone bridges. These bridges are made in variety of forms. In most forms the resistances, r, r_1 and r_2, consist of number of resistance coils or units carefully adjusted to various multiple of 10 and so arranged that they can be conveniently connected in and out c the circuit by means of plugs or switches. The resistances, r_1 and r_2 (Fig. 37 are commonly called the ratio arms and r the rheostat arm. A very earl form, which is still in use in small portable sets, is the **Postoffice** pattern shown diagrammatically in Fig. 38. Coils are cut out by short-circuitin them with plugs, so that there may be several plug-contact resistances of a unknown and variable amount in a given arm. In the **improved** form, show diagrammatically in Fig. 39, this objection is overcome by arranging th coils of the rheostat arm on the "decade" plan in which there are nine 1-ohm coils in the "units" division, nine 10-ohm coils in the "tens" division, et Any number of coils in a given division can be connected in circuit b changing only one plug. In many later types, the ratio-arm coils are al connected on the decade plan, which in addition to eliminating plug-conta resistance errors, permits interchecking the coils. Furthermore, the decad arrangement permits the use of sliding-brush or dial construction instea of plugs.

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120. Use of Wheatstone Bridges. Such bridges are best suited for measuring resistances of the order of about 1 ohm to 100,000 ohms. Accuracies of the order of 0.05 per cent. are obtainable with a first-class bridge if the unknown resistance is intermediate in value between the limits last named. The maximum precision is obtained when the four arms are equal; hence this condition should always be approached as nearly as possible by keeping r_1/r_2 small, and r_1 and r_2 as nearly equal to r as convenient. A galvanometer with 100 ohms to 500 ohms resistance will be satisfactory for nearly all classes of work. The resistance coils will dissipate about 1 watt without overheating, but care should be taken that the current does not become excessive when the ratio becomes large.

121. The slide-wire bridge is one of the earliest forms of the Wheatstone bridge. It is convenient and rapid where many similar measurements are to be made. It differs from the standard Wheatstone bridge in the respect that balance is obtained by varying the ratio r_1/r_2 instead of the resistance r (Fig. 37). This is accomplished by moving the contact, b, Fig. 40, along a wire, ac, which forms the resistance $r_1 + r_2$. This wire should be uniform in cross-section and homogeneous, so that the resistance per unit length will be constant. At exact balance, the ratio of the lengths $ab/bc = r_1/r_2$ and $r_x = (r_1/r_2)r$ as before. The precision is a maximum when the sliding contact is at the centre. When the slide wire is short, the precision decreases rapidly with settings toward either end. The length may be increased, in effect, by inserting equal resistances at n, n', which increases the sensibility, but also decreases the permissible difference between r and r_x.

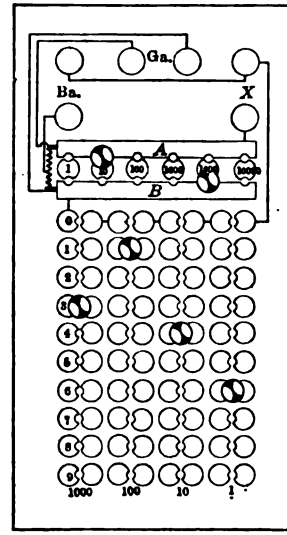


FIG. 39.—Wheatstone bridge—Improved "decade" form.

122. The Carey-Foster bridge is particularly adapted to the comparison of low resistances. The distinctive feature is the elimination of the contact resistance and other unknown resistances, in the arrangement shown in Fig. 40, by taking two readings. The bridge is first balanced with the contact at x. The resistances r and r_x are then interchanged and a balance obtained at x_1. If the resistance of the slide wire per unit length is ρ, then $r_x - r = \rho(x_1 - x)$. This method is especially suitable for comparison of standard resistances with each other and for temperature coefficient determinations.

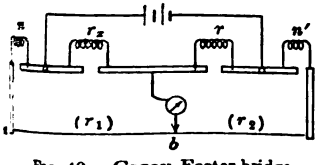


FIG. 40.—Carey-Foster bridge.

123. The Kelvin double-bridge is especially suitable for measurements of low resistances. It is the most generally used form, even in the most precise work, because of its accuracy and convenience. The principle is shown in Fig. 41. The resistance of the connection between r and r_x is made negligibly small and the bridge assumes the form of the Wheatstone bridge (Fig. 37) with the addition of an extra pair of ratio arms, α and β. When a balance is obtained:

$$\frac{r_x}{r} = \frac{r_1}{r_2} + \frac{d}{r}\left(\frac{\beta}{\alpha+\beta+d}\right)\left(\frac{r_1}{r_2} - \frac{\alpha}{\beta}\right) \qquad (12)$$

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In practice, r_1/r_2 is kept equal to α/β and the resistance d is made negligit small. Then $r_x = (r_1/r_2)r$, as in the Wheatstone bridge.

In the Wolff bridge, Fig. 42, the ratios r_1/r_2 and α/β are automatical adjusted simultaneously, by sliding contacts on the four dials. In the Lee and Northrup bridge, Fig. 43, both r and the ratio r_1/r_2 are adjusted.

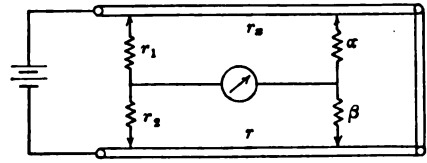


FIG. 41.—Diagram of Kelvin double bridge.

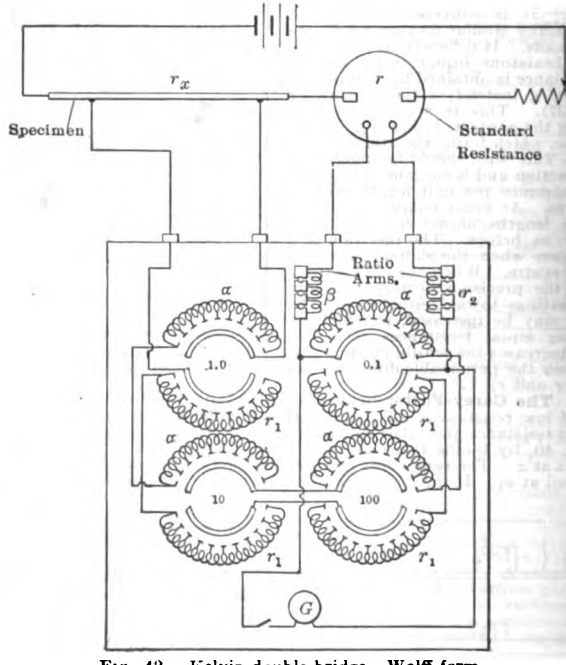


FIG. 42.—Kelvin double bridge—Wolff form.

124. Conductivity measurements. The specific conductance conductivity of a material is the reciprocal of the specific resistance resistivity. The relative conductivity is the ratio, expressed in per cent the specific conductance of the sample to that of a standard material. relative conductivity may be based on equal masses or equal volumes. former is in most common use because conductor metals are usually sold a weight basis (see Sec. 4).

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125. **Conductivity standards.** The present official standard of the A. I. E. E. is the **International Annealed Copper Standard,*** defined as follows:

Mass-resistivity at 20 deg. cent.:
0.15328 ohm (meter, gram)
875.20 ohms (mile, pound)

Volume-resistivity at 20 deg. cent. and 8.89 density:
1.7241 microhms (cm.³)
0.67879 microhms (in.³)
10.371 ohms (mil, foot)

For earlier standards of copper resistivity, see Sec. 4.

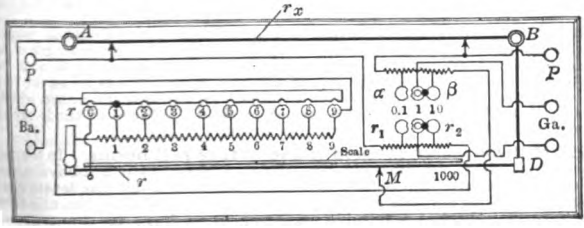


FIG. 43.—Kelvin double bridge—Leeds & Northrup form.

126. **Methods of measuring conductivity.** Conductivity may be determined by calculation from the measured resistance or by **direct** comparison with standards of conductivity. When the conductivity is to be calculated from the resistance, the specimen must have a uniform cross-section. The resistance of a definite length is carefully determined, the temperature being noted. Then the resistance of a piece of copper having 100 per cent. conductivity and the same weight and length as the specimen (or, for volume basis, the same cross-section and length) is calculated from the stated definition of the standards. The ratio of these two resistances is the conductivity of the specimen. The direct comparison methods employ conductivity bridges which are adaptations of the Kelvin bridge. They are intended for commercial work, where speed combined with moderate accuracy is important.

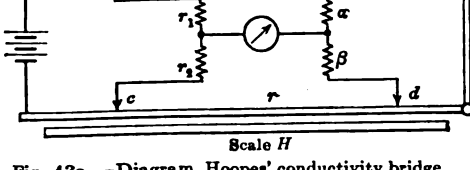


Fig. 43a.—Diagram, Hoopes' conductivity bridge.

127. **In the Hoopes conductivity bridge,**† the conductivity of a specimen of wire is read directly from a graduated scale. The principle is shown in Fig. 43a where r_x is the specimen to be measured, r a standardized wire and a, b, α, β, are the double ratio coils. All four of the latter are made equal,

*Standardisation Rules, A. I. E. E., Dec. 1914 and Bureau of standards Circular No. 31, Copper Wire Tables; 2d edition, 1913.

†Hoopes, Wm. "A New Apparatus for Making Direct Measurements of Electrial Conductivity," *Electrical World and Engineer*, Nov. 14, 1903.

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about 300 ohms each, in order to eliminate the effect of contact resistan at *a*, *b*, *c* and *d*. When the bridge is balanced, the resistance between and *d* on *r* is equal to that between *a* and *b* on r_x. The unknown specime r_x is cut to a certain definite length and carefully weighed. The contac *d*, on the standard is then set at the point indicated on the carefully graduate scale *H*, which corresponds to this weight. Then the resistance, *cd*, is equ to that of a piece of wire having 100 per cent. conductivity, a length equal 100 parts in the scale *I* and the same weight per unit length as r_x. Conta *b* is shifted until a balance is obtained and the conductivity is read direct from scale *I*, 100 scale divisions corresponding to 100 per cent. conductivit One standard is provided for every three sizes of wire in the Americ (B. & S.) gage. The standards are usually of the same material as that bein tested, so that the temperature does not have to be observed.

128. Resistance of rail joints. The testing of rail bonds consis in determining, either, (a) the ratio of the resistance of a given length of rai including a bonded joint, to that of the same length of continuous rai or (b) the length of solid rail which has the same resistance as the join The resistance of rail bonds is usually expressed in the latter manner, wheth measured in that way or by the former method. Three methods are em ployed: millivoltmeter, bridge, and opposition.

129. Millivoltmeter method of measuring rail bonds. In the mill voltmeter method, simultaneous readings are taken with 2 millivoltmeter one connected across the bond and the other across a definite length of rai If the current fluctuations are not too rapid, only one instrument is nece sary, provided there is a suitable arrangement of keys to change the co nections in quick succession.

130. In the Roller bond tester the principle of the **slide wire form Wheatstone bridge** is employed (Fig. 44). Balance is obtained by movi the contact *B* back and fort At balance, $ab/bc = (r_1+m)/(r_2+n)$; where *ab* = resistan of bond and *bc* = resistance the standard length of ra The resistances r_1 and r_2 ha the effect of extending the slid wire and providing greate accuracy (see Par. 121). I the actual instrument, the slid wire takes the form of a circ and the scale is graduated give the resistance directly i terms of the number of feet the solid rail being tested.

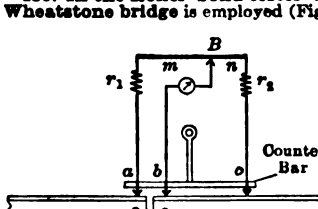


FIG. 44.—Diagram, Roller bond tester.

131. The Conant bon tester is an example of th class in which the drop across the joint is opposed to that across a length solid rail, the outer contact on the latter (*c*, Fig. 44) being moved along unt the two potentials are just equal and opposite. The detector is a telephor receiver in series with a make and break device operated by a clock.

132. Insulation resistance. The resistance of insulating materia is usually measured by deflection methods. In the case of resistanc of the order of 1 megohm and less, a Wheatstone bridge may be used, bu the accuracy will be low because of the extreme ratio required (Par. 12 and the low insulation resistance of the bridge.

Two general classes of deflection methods are used: (1) direct deflectio and (2) leakage. The direct-deflection methods involve a simple applicatio of Ohm's law, the current being measured with a voltmeter used as an an meter or with a galvanometer.

133. Direct-deflection method (insulation resistance). Whe the resistance is of the order of 1 megohm, an ordinary voltmet will give results which are sufficiently accurate for most purposes. Tw readings are taken, one with the voltmeter directly across the battery generator, and the other with the resistance to be measured connected series with the voltmeter. The resistance is $R = r_v(d-d_1)/d_1$; where r_v

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resistance of voltmeter (the greater the resistance per volt, the higher the precision), d = deflection of voltmeter in first reading, d_1 = deflection in second reading. Obviously a portable galvanometer with series resistance may be used as a voltmeter.

When the resistance is moderately high, a high-resistance reflecting D'Arsonval galvanometer is employed. Fig. 45 is a simplified diagrammatic arrangement for measuring the insulation of a cable. The measurement is made as follows: after the galvanometer shunt, s, is set at the highest value (Par. **29** and **30**) and r_s is short-circuited, the main circuit is closed. The shunt is then decreased until the largest readable deflection is obtained. A reading is taken after 1 min. This procedure is then repeated with the standard resistance r_s (usually 0.1 or 1 megohm) in circuit and the specimen short-circuited. The resistance of the specimen in megohms is: $R = G/d_1 s$; where d_1 = first reading, s = multiplier corresponding to the shunt setting

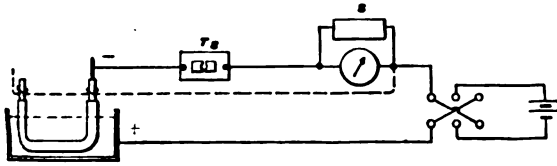


FIG. 45.—Diagram, insulation resistance of cable.

(that is, 1, 10, 100, 1,000 or 10,000) and G = galvanometer megohm-constant (Par. **24**) as obtained from the second measurement. The constant is $G = dr_s$; where d = deflection, s = shunt multiplier, r_s = standard resistance in megohms. The conductor is preferably negative to the sheath or water.

134. Leakage method of measuring insulation resistance. Very high resistances such as the resistance of porcelain and glass, and surface leakage resistance of line insulators, are best measured by the method of leakage, also known as the loss-of-charge method. This method is based on the theory that if the insulation resistance of a condenser is infinite, it will retain a charge indefinitely; whereas if the resistance between the condenser terminals (either the internal resistance or a resistance connected externally) is finite, the rate of loss of the charge (or leakage) will be a measure of that resistance. The principle of this method is shown in Fig. 46 where the resistance to be measured, r, is connected in parallel with a condenser C. Key a is closed and immediately opened, thus charging the condenser. Key b is closed immediately after a is opened and the deflection, d_1 of the ballistic galvanometer noted. The process is repeated, a being left open a definite time, t seconds, before b is closed and a second deflection d_2 observed. The resistance in megohms is then:

$$r = \frac{t}{2.303\, C \log_{10}\left(\frac{d_1}{d_2}\right)} \quad \text{(megohms)} \qquad (13)$$

where C is the capacity of the condenser in micro-farads.

The insulation resistance of the condenser is usually not infinite. Correction should be made by measuring the resistance of the condenser in a similar manner, r being disconnected. If r_2 is the resistance of the condenser and r_1 the resistance obtained above in Eq. 15, the corrected value is

$$r' = \frac{r_1 r_2}{r_2 - r_1} \quad \text{(megohms)} \qquad (14)$$

135. Measurement of specific resistance (resistivity) of solid insulating materials. This is obtained by calculation from the resistance between two similar metallic electrodes of known area in intimate contact with the opposite and parallel faces of a specimen of the material. Tin-foil makes convenient and satisfactory electrodes if backed with blotting paper and sufficient weight to insure good contact.

136. The specific resistance of liquid insulating materials may be approximately determined by pouring a specimen into a round glass cylinder

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or graduate in which two circular, closely fitting disc electrodes are supported One of the electrodes should be movable so that the resistance of column of several different lengths can be measured. The first measurement should be taken as the zero or base reading and the results checked by calculation of the increase in resistance and the corresponding increase in the spacing of the electrodes at different settings.

137. Precautions in measuring insulation resistance. In the measurement of the insulation resistance of specimens having electrostatic capacity, sufficient time should be allowed for the specimen to become charged that is, until the deflection becomes constant, at minimum value. This usually takes place within min., except in long lengths of cable. In order to eliminate uncertainties in this connection, it is customary to specify 1-minute "electrification."

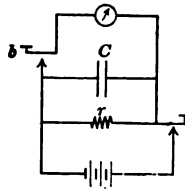


FIG. 46.—Leakage method of measuring insulation resistance.

As the apparent insulation resistance varies with the testing potential, one hundred volts is usually prescribed as the minimum pressure that should be used.

Leakage over the surface of wire or other specimens may be a source of much trouble in damp weather. In wires and cables, the lead or braid should be removed for 2 or 3 in. from the ends and the exposed insulation coated with hot, clear paraffine; or, just before measuring, these prepared ends may be carefully dried with an alcohol, Bunsen or other flame free from carbon. As a further precaution, a "*guard*" *circuit* may be arranged as shown by the dotted lines in Fig. 45. This consists of a few turns of fine copper wire twisted around the insulation close to the copper conductor and connected to the battery side of the galvanometer. In the case of solid specimens, the twisted wire is replaced with a ring of tin-foil as shown in Fig. 97.

Specimens having electrostatic capacity should be put in a neutral condition by rapidly reversing the current a number of times, beginning with a low rate of reversals and gradually increasing. Where the capacity is high it may be advisable gradually to decrease the applied voltage at the same time.

The side of the circuit which contains the galvanometer should be well insulated throughout. The battery also should be insulated as thoroughly as possible; this is a relatively easy matter when dry cells are used. The important point is to insure that all current passing through the specimen, and only that current, passes also through the galvanometer.

The galvanometer should, preferably, have a high resistance (order of 1,000 ohms) and a megohm sensitivity (Par. **23** and **24**) of several hundred megohms. The temperature should always be noted, because of the large coefficient which most insulating materials have.

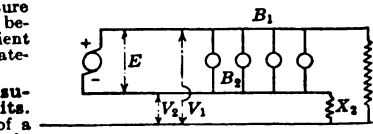


FIG. 47.—Insulation resistance of "live" circuits.

138. Measuring the insulation resistance of circuits. The insulation resistance of a "dead" circuit is conveniently made by the voltmeter method. When there is no source of e.m.f. available, various portable instruments described below are especially applicable and convenient. (Also see Sec. 21.)

When the circuit is "alive" the following method may be used.* Fig. 47 represents diagrammatically a system with lamps and motors connected. The resistances X_1 and X_2 represent the insulation resistance from the positive and negative sides respectively to ground.

$$X_1 = \frac{R(D - d_1 - d_2)}{d_2}, \text{ and } X_2 = \frac{R(D - d_1 - d_2)}{d_1} \text{ (ohms)} \quad (1$$

* Northrup, E. F. "Methods of Measuring Electrical Resistance" McGraw-Hill Book Co., p. 210.

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where R = resistance of voltmeter; D = deflection (scale divisions) corresponding to circuit voltage, E; d_1 = deflection corresponding to V_1: d_2 = deflection corresponding to V_2.

Should the system be continuous current, a D'Arsonval-type voltmeter is preferable; if it be alternating current, an electrodynamometer-type instrument should be used. This method in general will measure 1 megohm with sufficient accuracy to check specifications. If the resistance is over 1 megohm a galvanometer method is more accurate.

139. Portable instruments for the direct measurement of insulation resistance are classed either as testing sets or ohmmeters. **Testing sets** range from a simple Wheatstone bridge with self-contained galvanometer and battery, to elaborate cable-testing sets which include a small Wheatstone bridge, a standard 0.1 megohm resistance for insulation tests by the series galvanometer method, and a standard condenser for capacity measurements.

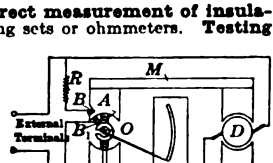


FIG. 48.—Eversheld Megger.

Ohmmeters indicate the resistance directly. In instruments of the **Sage** type, the principle of the slide-wire bridge is employed. A scale beneath the slide wire is calibrated directly in ohms, so that when balance is obtained, the resistance is read off directly. The range can be extended by means of a number of different ratio arms, a separate scale being provided for each. Where alternating current is necessary, as in measuring electrolytes, an induction coil is introduced in the battery circuit and a telephone replaces the usual galvanometer. Ohmmeters are specially convenient for quantity (factory) testing.

The Eversheld "Megger" is an ohmmeter which indicates the resistance by the movement of a pointer over a calibrated scale.* The principle employed is indicated in Fig. 48, where A is a coil in series with the resistance to be measured and B, B_1 are coils, which, with the resistance R, are connected to a hand-driven generator D. All three coils are rigidly coupled together and are connected to the circuit by fine copper strips which exert no controlling force. When the generator is actuated a current flows through coils B, B_1 proportional to the e.m.f. generated. If the external circuit is open, B and B_1 are deflected to the position where the least flux from the permanent magnets M M_1 will intersect them, that is, opposite the gap in the C-shaped iron piece about which the coils A and B_1 move. The pointer then stands at "infinity" on the scale. If now a finite resistance is connected across the terminals, the current flowing in A will produce a deflecting torque toward the position shown in the figure, and, as the system moves, the coils B and B_1 exert an opposing torque of constantly increasing magnitude. Hence the system comes to rest at a point where the two forces are balanced, the position depending upon the amount of the external resistance.

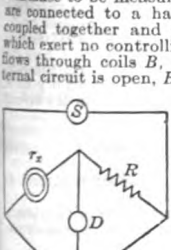


FIG. 49.—Resistance of electrolytes—Bridge method.

140. Measurement of the resistance of electrolytes. Electrolyte resistances are more difficult to measure than metallic resistances because of the counter e.m.f. of polarisation. The several methods in use are based on the method first proposed by Kohlrausch, that is, a simple bridge arrangement in which alternating current is employed instead of direct current.

A standard Wheatstone bridge may be used, but a **slide-wire type** is found more convenient, especially if the slide wire is a long one wound spirally on a marble cylinder. When such slide-wire resistance is a separate piece of apparatus, a bridge may be easily made up and used as indicated in Fig. 49 where R is a non-inductive resistance box and r_x

*Biddle, J. G. Circular No. 740; Philadelphia, Pa., 1910.

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the electrolyte. If the slide-wire scale is divided into 1,000 parts, the resistance of the electrolyte is, at balance,

$$r_x = \left\{ \frac{a}{(1000-a)} \right\} R. \qquad \text{(ohms)} \qquad (16)$$

If the source is alternating-current power of commercial frequencies an alternating-current galvanometer (reflecting electrodynamometer) may be used, the fixed coils being connected in series between the source, S, and the bridge and the moving coil in place of D (Fig. 49). A **Vreeland oscillator** (Par. **246**) is very satisfactory as a source of energy because the wave form is a pure sine curve and the frequency is sufficiently high for a telephone at S.

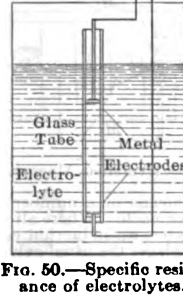


FIG. 50.—Specific resistance of electrolytes.

141. Specific resistance of electrolytes. Where the specific resistance or resistivity is required, a column of the liquid of known dimensions must be isolated. Fig. 50 shows a satisfactory method.* The glass tube is about 20 cm. long, 1 cm. internal diameter and open at both ends. The electrodes are of gold or platinum, the lower one being fixed in position and perforated, while the upper one is adjustable. The average cross-section must be carefully determined, preferably by volumetric measurement with mercury. The temperature is readily kept constant by stirring the liquid in the containing vessel.

142. Internal resistance of batteries. This measurement involves difficulties because of polarisation. One simple direct-current method is as follows. The e.m.f. of the cell or battery is first measured on open circuit. The circuit is then closed through a known resistance and the e.m.f. measured again quickly before polarisation begins. The resistance is

$$R_x = \frac{R(E-E_1)}{E_1} \qquad \text{(ohms)} \qquad (17)$$

where R = known resistance, E and E_1 = voltage before and after closing circuit, respectively.

This method assumes that the internal resistance will remain constant under all conditions, which is not always the case, especially in dry cells. In a modification of this method, both readings are taken with the circuit closed, but with two slightly different values of R. Then

$$r_x = \frac{(E_1-E_2)R_1R_2}{E_2R_1-E_1R_2} \qquad \text{(ohms)} \qquad (18)$$

where R_1 and E_1 are the first resistance and e.m.f., respectively, and R_2 and E_2 are the corresponding values with the second resistance.

In general, such direct-current methods should be used only with primary batteries of very low resistance and with secondary or storage batteries. Alternating-current methods are more reliable.

143. Alternating-current method of measuring internal resistance of batteries. The Kohlrausch bridge shown in Fig. 49 can be used in this method, by inserting the cell or battery in place of the electrolyte cell. Without resistance R′ connected, the resistance of the cell will be

$$r_x = \frac{a}{(1000-a)} R \qquad \text{(ohms)} \qquad (19)$$

If the resistance R' is connected, the resistance of the cell with a current corresponding to R' flowing, will be

$$r_x = \frac{aR'R}{(1000-a)R-Ra} \qquad \text{(ohms)} \qquad (20)$$

144. Effective resistance of alternating-current circuits. The passage of alternating current through a circuit is opposed by the ohmic resistance,

* Northrup, E. F. "Methods of Measuring Electrical Resistance," McGraw-Hill Book Co., p. 241.

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also by the resistance-equivalent of all the energy losses except the loss due to ohmic resistance, and by the reactance. The "ohmic resistance" is the resistance to the passage of continuous current and is therefore measured with continuous current by the methods previously described.

145. The effective or alternating-current resistance is that value of resistance which represents the total energy loss. It includes in addition to the ohmic resistance, the effect of any other source of lost energy, such as iron losses in a magnetic circuit, dielectric losses, and induced currents in a neighboring circuit. This effective resistance produces a potential drop which is in phase with the current. The simplest method of determining it is from the relation: $W = I^2R$, where W = watts measured with a wattmeter, I = current (amperes) and R = alternating-current resistance (ohms).

146. Measurement of effective resistance. When the power is small, current large and power factor low, an ordinary electro-dynamometer (Par. 33) may still be used. The exciting current must be in phase with the current through the unknown resistance in order that the reading obtained with the moving coil across the resistance will be $W = I^2R$. This condition may be established in several ways: (a) by connecting the fixed coils across a series non-inductive resistance in the circuit (first compensating for inductance if necessary, see Par. 169); (b) by connecting the fixed coils to a phase shifter (Par. 213) which is first adjusted (the moving coil being connected to a non-inductive resistance in series with the resistance to be measured) until a maximum deflection is obtained. A more sensitive method is to connect a condenser in series with the fixed coils and adjust the phase shifter for zero deflection. The dynamometer can be calibrated on a non-inductive resistance or on continuous current.

147. Wheatstone-bridge methods of measuring effective resistance may also be used by providing facilities for obtaining a balance for both resistance and inductance. The two "ratio" arms should be non-inductive, and the "rheostat" arm should contain both a variable resistance and a variable inductance, so that complete balance may be obtained. The detector must indicate both states of balance and should be an electro-dynamometer instrument or a synchronously driven reversing key (Par. 39). When using the former instrument, a resistance balance is obtained with the fixed coils excited from the same circuit, that is, in series with the bridge or across a shunt. Inductance balance is obtained with the fixed coils excited from a circuit 90 deg. from the first, the moving coils being connected across the bridge in the usual manner.

148. The measurement of reactance and impedance of an alternating-current circuit may be effected very simply with an ammeter, a voltmeter and a wattmeter, as indicated by the following relations, where Z = impedance in ohms, X = reactance in ohms, R = alternating-current resistance in ohms, W = power in watts, I = current in amperes, E = total potential-drop in volts, $\cos\theta$ = power-factor = W/EI.

$$(a)\ Z = \frac{E}{I},\quad (b)\ Z = \frac{W}{(I^2\cos\theta)},\quad (c)\ X = \frac{W}{I^2}\tan\theta,\ (d)\ X = Z\sin\theta \qquad (21)$$

POWER MEASUREMENTS

149. General considerations. When a quantity of electricity, q, is passed through a circuit against a difference of potential, e, the work done, that is, the amount of energy expended, is ge. Power is the rate of expending energy and at any instant is $e\partial q/\partial t = ie$, because $\partial q/\partial t = i$, where i and e are the instantaneous values of current and potential, respectively. Power expressed in watts is the energy expended per second, or, $W = QE/t$, where Q = quantity in coulombs, E = potential in volts and t = time in seconds.

150. Continuous-current power. In a circuit supplied by a battery or a continuous-current generator, energy is expended at a uniform rate; hence, $e\partial q/\partial t = QE/t = IE$, where Q = quantity in coulombs, E = e.m.f. in volts, t = time in seconds and I = current in amperes. The power in such circuits is usually determined by measuring the current and the potential, simultaneously. Wattmeters may of course be used, but they are somewhat less accurate than permanent-magnet instruments.

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151. Pulsating power. Where there are instantaneous variatio in the current and the potential, the power varies from instant to instan The average power will be the average of the products of corresponding insta taneous values of current and potential and it can be measured with *strict* a curacy only with watt-meters of the dynamometer type. In rectifier circuit the power consumption of a storage battery or a motor can be approximate measured with a voltmeter and an ammeter of the permanent magnet typ Such instruments would give a more nearly correct result than dynamomet instruments. On the other hand, the reverse will be the case with a load of i candescent lamps or heating devices. The error will depend upon the wa shape and the character of the load. The safe method is to use a dyn mometer-type wattmeter.

152. Alternating-current power. The power in an alternating-cu rent circuit, at any instant, is the product of the current and potential that instant. When the load consists only resistance, the current wave, I, and the pote tial wave, E, are in phase as shown in Fig. 5 and the power-factor is 100 per cent. or unit If the products of the instantaneous values current and potential are plotted, the curve is obtained. The average value of this cur is the power equivalent of a continuous cu rent producing the same effect. Also, W EI, where W = ave age watts, E = me effective volts and I = mean effective ampere These values of potential and current are i dicated by instruments in which the deflections are proportional to t square of the current.

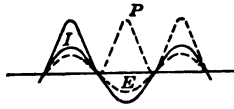


FIG. 51.—Relation of current, e.m.f. and power in a.c. circuit.

153. When the power-factor is less than unity, due to the fact th the circuit contains inductance or capacity (or the equivalent), the curre and the potential will not be in phase. In the case of an inductive load, t current will lag behind the potential, as shown in Fig. 52. The pow curve then will not be all on one side of the axis, but a part will be negativ If the current lags sufficiently, Fig. 53, the power curve will be positive h of the time and negative the other half; the average power will then be ze (or zero power-factor). This difference in phase, or time relation betwe the current and the potential, is called the phase angle and is usually e pressed in degrees, an entire cycle being 360 deg. If the current and t

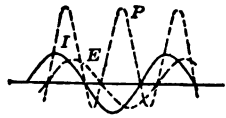


FIG. 52.



FIG. 53.

FIGS. 52 AND 53.—Relation of current, e.m.f. and power in a.c. circuit.

voltage are sinusoidal, the average value of the power is $W = EI \cos$ where ϕ is the phase angle. Therefore if the current and the potential a not in phase, it is necessary to know the value of the phase angle if the pow is to be determined from the current and the potential. Fortunatel power can be measured directly with **wattmeters**, which not only aut matically integrate the power curve, but take into account the factor, cos

154. Precision measurements of power must be made with an instr ment which is equally accurate on continuous and alternating currents, order that it may be calibrated on continuous current. Such measuremen are most accurately made with **reflecting electrodynamometers** which deflections are measured by means of a mirror, with a lamp and scal (See Par. **32**, **64** and **97**.) The fixed coils are often divided into several se tions, which may be connected in various series and parallel combinatio to give large deflections over a wide range of power intensities. Instrumen of this type made by the General Electric Company have current capa ities from 5 amp. to 125 amp. and above, with corresponding sensitiviti

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of 10 and 200 watts respectively at full scale deflection, with a 50-cm. (19.7 in.) scale at 100 cm. (39.4 in.) distance.

155. The Westinghouse "precision" wattmeter is similar to the corresponding ammeter (Par. 99), except that the moving coils are wound with fine wire and are connected across the line instead of in series with the fixed coil. There are usually two or three current ranges, and the series resistance for the moving coil is mounted in a separate box. It therefore can be used with a wide range of voltages, from 10 volts up. Although considerable metal is used in the construction of this instrument, it is so arranged that the eddy-current error is not appreciable at commercial frequencies.

156. The Duddell-Mather type of wattmeter as made by Paul is a carefully constructed, semi-portable, secondary standard in which the current element comprises four fixed coils connected in series, and the potential or moving element consists of four coils connected in series, all astatically arranged. The moving element is suspended by a silk fibre and a spiral spring furnishes the controlling force. It is a torsion-head instrument like the Westinghouse wattmeter.

157. Commercial indicating wattmeters are made in two general forms, the electrodynamometer type and the induction type.

158. The Weston model-16 and the General Electric type P₂ instruments are well-known examples of the **electrodynamometer class.** Fig. 54 shows the general arrangement. The current or series element consists of two fixed coils wound with heavy wire or strip, which are connected in series with each other and with the main circuit. The potential or shunt element is a moving coil mounted on a shaft supported between jewel bearings and placed between the two fixed coils. This coil consists of a large number of turns of fine wire, as in voltmeters; it is connected in series with a relatively large amount of non-inductive resistance, across the main circuit. The controlling force comprises one or more spiral springs.

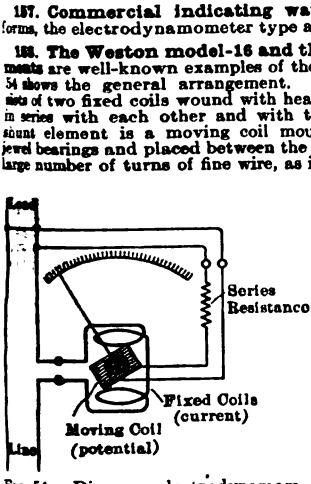


FIG. 54.—Diagram, electrodynamometer type wattmeter.

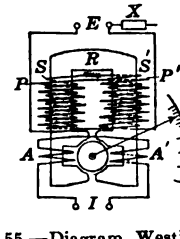


FIG. 55.—Diagram, Westinghouse induction type wattmeter.

159. The inclined-coil type of wattmeter (General Electric Company) is similar in principle (Par. 158), but the centre lines of the fixed coils and the moving coil make an angle of about 45 deg. with each other, instead of 90 deg., the object being to make the scale more open, or more uniformly graduated.

160. The Westinghouse portable wattmeter is the most important example of **induction-type** wattmeters. The principle is exactly the same as that of the induction watthour meter (Par. 202); but instead of allowing the moving element to rotate, the torque is opposed by a spiral spring and hence the deflection is proportional to the power. Fig. 55 shows the schematic arrangement, where AA' are the current or series coils, PP' the potential or shunt coils and SS' the compensation coils by means of which, together with the adjustable resistance, R, the exact quadrature relation is obtained as in watt-hour meters. This type is also made in polyphase form by having two sets of current and potential elements acting on a common

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moving disc, or drum, as in the polyphase watt-hour meter. It is obvious that instruments of this type are limited to the frequency for which they are designed.

161. The Whitney wattmeter operates on the dynamometer principle (Par. 158) except that it is a torsion-head instrument, the moving element being kept in a fixed position by twisting the torsion head to which the control spring is attached. The pointer attached to this head moves over the scale. This method permits using a very long scale, extending around a full circle.

162. Wattmeters for switchboard use employ both the electrodynamic and the induction principles. Weston instruments are similar to the portable electrodynamometer instrument (Par. 158). The General Electric edgewise type "H" instruments are dynamometer types while type I is of the induction type. Westinghouse switchboard instruments are also induction type.

163. The calibration of wattmeters of the dynamometer type should be done with continuous current. It is customary to make such tests at a fixed potential, usually 100 or 200 volts, and to vary the current to give the required watts. The potential is held constant at the desired value by means of one standard (standard voltmeter or potentiometer) and the current is read on another standard (standard ammeter, or potentiometer with standard resistance). It is more convenient to obtain the potential and the current from separate sources, because the process of adjustment of one circuit will not affect the other. In the case of instruments of large capacity this method economises energy, because only three or four volts are necessary for the current circuit.

164. Calibration of induction-type wattmeters. These instruments must be checked on alternating current of the frequency for which they are designed. This check is made by comparison with a secondary standard, which in turn is checked on continuous current. Polyphase instruments may be checked as single-phase instruments by connecting the current circuits in series and the potential circuits in parallel. In the case of induction-type instruments stray magnetic flux from one element may affect the other, in which case the calibration should be made on a polyphase circuit.

165. The inductance error in wattmeters may, under certain conditions, become very important. While the theory of the electrodynamometer type of wattmeter assumes that the potential circuit is non-inductive, this is not strictly true in the actual instrument because of the inherent inductance of the coils. Ordinarily, however, the non-inductive series resistance is sufficiently large to make the effect of this inductance negligible at ordinary frequencies and power-factors. But with low power-factors, the lag angle in the potential circuit may have to be considered. The power in an alternating-current circuit is $W = EI \cos \theta$, where W = power, I = current, E = e.m.f. and cos θ = power-factor of circuit. When the power-factor is unity, I and E are in phase, but the potential-circuit current lags slightly behind E, thus producing the effect of a small power-factor. If, for example, the lag-angle, ϕ, is 2 deg., cos $\phi = 0.9994$—a negligible error. If the line power-factor is 50 per cent., the lag angle in the wattmeter, ϕ, is $(60 - 2) = 58$ deg. The cosine of 60 deg. is 0.50 while the cosine of 58 deg. is 0.53, thus introducing an error of 6 per cent. (See Par. 169 for compensation and Par. 170 for correction for inductance.)

166. The stray-field error in unshielded, non-astatic, electrodynamometer wattmeters may be anything from zero to 25 per cent. with an alternating magnetic field of 5 lines per square centimeter, and from zero to 75 per cent. at 10 lines, depending upon the direction of the field and the coil deflection. A shield, properly made and placed, is extremely efficient, reducing the effect of a field of 20 lines per square centimeter to practically zero, without introducing eddy current or other errors.

Wattmeters of the Kolvin balance type, in which the coils are astatically arranged, are practically immune from these troubles except in an intense field which is not uniform throughout the space occupied by the moving system; such a condition may arise, for example, when the wattmeter is close to a conductor carrying a very large current. Induction-type instruments employ much stronger field strengths and are not appreciably affected except by very strong fields.

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167. Wattmeter connections to line. Care should be taken so to connect a wattmeter into the main circuit that the moving-coil end of the potential circuit and the current coil are on the same side of the circuit being measured. Otherwise there may be sufficient electrostatic attraction between the two windings to produce an error; or, if the potential is sufficiently high, the insulation between the windings may be broken down. The latter may be guarded against by connecting the binding post at the moving-coil end of the potential circuit to the proper current post with fine fuse wire.

168. Correction for wattmeter losses or energy consumption. Where small quantities of power are being measured, the losses in the circuits of the instrument itself should be taken into account. It will be noted in Fig. 56 that the instrument is measuring its own current circuit loss, or series I^2R loss. If the instrument loss cannot be neglected, it is better to

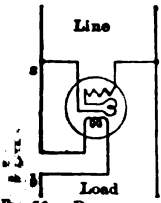


FIG. 56.—Power measurements in single-phase circuits with wattmeter.

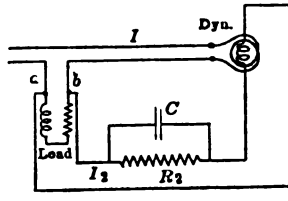


FIG. 57.—Electrodynamometer arrangement for measuring small amounts of power.

connect the potential circuit to the load side (*b* instead of *a*) and include the potential circuit loss in the measurement instead of the current circuit loss, because the former not only remains constant but is more easily calculated. Wattmeters are often arranged to correct or compensate automatically for this loss by means of a few turns on the fixed coil, connected in series with the potential circuit and in opposition to the fixed coil. This arrangement cannot be used with shunt-type instrument transformers nor when checking the wattmeter with separate sources of e.m.f. and current. A separate connection is usually provided, however, for this purpose. In general it is safer always to use this "independent" connection, making allowance for the potential loss, when necessary, by calculation.

169. Measurement of very small amounts of power. Where the power is extremely small, only a few watts, reflecting electrodynamometers are most accurate. This is especially true when the power-factor is low, the

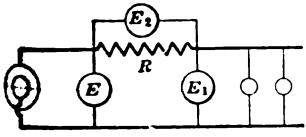


FIG. 58.—Power in single-phase circuit, three-voltmeter method.

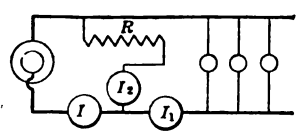


FIG. 59.—Power in single-phase circuit, three-ammeter method.

potential high and the current low, or *vice versa*, as for example the losses in alternating-current conductors, in dielectrics, instrument circuits and magnetic circuits. The fixed coils may be connected directly in series with the main circuit or to a non-inductive shunt in the circuit. At low potentials, the series resistance in the moving-coil circuit may not be sufficient to eliminate the effect of inductance but this can be accomplished by shunting the resistance with a condenser as shown in Fig. 57. When the potential circuit is short-circuited at *a*, *b*, the capacity *C* or resistance R_2 is adjusted until there is no deflection with full current in the fixed coil ($L_{dyn.} = CR_2^2$). Calibration is of course made with continuous current.

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170. Measurement of power in a single-phase circuit. One wattmeter connected as shown in Fig. 56 will read true watts. The power may also be measured without the use of a wattmeter, by three voltmeters or three ammeters.

In the "**three-voltmeter**" method, a known non-inductive resistance, R, is connected in series with the load as shown in Fig. 58, where E, E_1 and E_2 are points where voltmeter readings are to be taken. The power in watts is

$$W = \frac{E^2 - E_1^2 - E_2^2}{2R} \qquad \text{(watts)} \qquad (22)$$

Similarly, in the "**three-ammeter**" method, Fig. 59, the power in watts is

$$W = R\left(\frac{I^2 - I_1^2 - I_2^2}{2}\right) \qquad \text{(watts)} \qquad (23)$$

171. Two-phase, four-wire circuit (not interconnected). Two wattmeters are connected as shown in Fig. 60, the conditions being equivalent to two single-phase circuits. The total power is obviously the arithmetical sum of the readings of the two instruments.

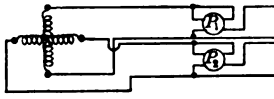


FIG. 60.—Power in two-phase, four-wire circuit (not interconnected).

172. Two-phase, three-wire circuit.—Two wattmeters should be connected as shown in Fig. 61, the total power being the *algebraic* sum of the two readings. This connection is correct for all conditions of load, balance and power-factor. One wattmeter may be used as in Fig. 62, provided there is no load across the outer conductors and the phases are *balanced* as to load and power-factor.

173. Two-phase, four-wire, interconnected circuit. Three wattmeters can be used, connected as in Fig. 63, the total power being the *algebraic* sum of the three readings. This connection is correct under all conditions of load, balance and power-factor. Two wattmeters, one in each phase, will give the true power only when the load is balanced.

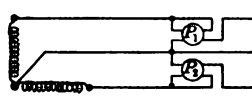


FIG. 61.—Power in two-phase three-wire circuit.

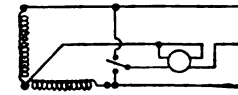


FIG. 62.—Power in two-phase, three-wire circuit.

174. Three-phase, three-wire circuits. Two wattmeters may be used connected as in Fig. 64, the total power being the *algebraic* sum of the two readings under all conditions. If the load is *balanced*, each instrument will indicate half the total power at unity power-factor and at 50 per cent. power-factor one instrument will indicate the total power, the other instrument reading zero. At less than 50 per cent. power-factor, one instrument will read negative. (See Par. **209** for method of verifying power-factor.)

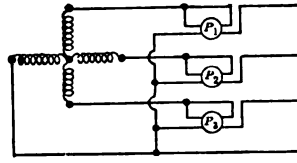


FIG. 63.—Power in two-phase, four-wire interconnected circuit.

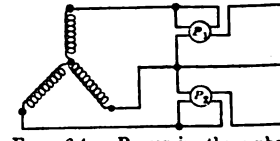


FIG. 64.—Power in three-phase three-wire circuit, two wattmeters

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175. Three-phase, three-wire circuits, balanced load. When the load is *balanced* the power may be measured with one wattmeter by the following methods.

(a) With **"star" box** or artificial neutral as shown in Fig. 65. The total power is three times the reading of the wattmeter. The resistance in each leg of the star box should be non-inductive and small compared with that of the potential circuit of the wattmeter, so that the current taken by the latter will not disturb the potential at the neutral point, *O*.

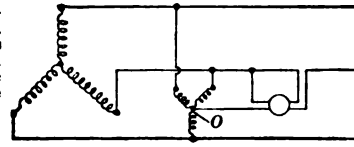


FIG. 65.—Power in three-phase, three-wire circuit, one-wattmeter, with "star" box.

(b) With **"Y" box** as shown in Fig. 66. The total power is three times the wattmeter reading. The arrangement is similar to (a), one leg of the star box being replaced with the potential circuit of the wattmeter itself. The other two legs have the same impedance as the potential circuit of the wattmeter.

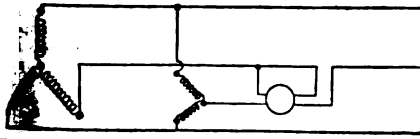


FIG. 66.—Power in three-phase, three-wire circuit, one wattmeter, with "Y" box.

(c) With a **"T" reactance coil** as shown in Fig. 67. The total power is twice the wattmeter reading. The impedance of the reactance coil must be small compared with that of the potential circuit of the wattmeter, so that the current taken by the potential circuit will not disturb the potential at *O*.

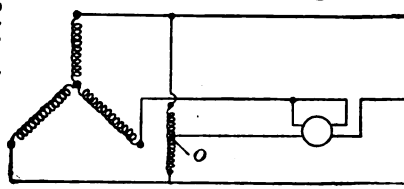


FIG. 67.—Power in three-phase, three-wire circuit, one wattmeter, with "T" reactance coil.

176. Three-phase, four-wire circuits. Three wattmeters are used as shown in Fig. 68. The total power is the *algebraic* sum of the three readings. This method is correct under all conditions of load, balance, and power-factor. A three-phase, "star" system with a grounded neutral is virtually a four-wire system and the power should be measured with three wattmeters. Obviously, if the load is balanced, one wattmeter can be used, the total power being the indication of the wattmeter multiplied by three. The current coil should be connected in series with one conductor or phase wire and the potential coil between that conductor and the neutral.

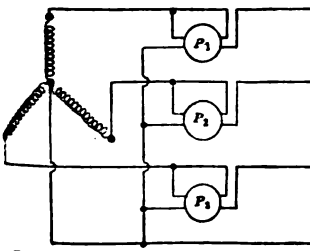


FIG. 68.—Power in three-phase, four-wire circuit.

177. "N"-phase circuit. In any system whatsoever, of "n" phases, the true power may be measured by connecting a wattmeter in each phase, the current coil being in series with the line and the potential coil connected between that line and any common

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point *P* of the system, which may or may not be the neutral. The tota power for any load condition is the algebraic sum of the readings of all of th wattmeters so connected.*

178. Power measurements on high-voltage circuits should preferabl be made with series-type and shunt-type instrument transformers. If th instrument wattmeter is connected directly to the circuit with series re sistance in the potential circuit, the circuit should be grounded at th instrument in order to avoid errors of electrostatic attraction, and also pos sible injury to the instrument or the observer. The current-capacity limi of commercial wattmeters is about 200 amp, beyond which series trans formers with 5-amp. instruments are used, irrespective of potential.

179. Corrections where instrument transformers are used in accu rate power measurements. In every case the **true ratio** and **phase angl** should be known (Par. **79** and Par. **104, 105**). The general effect of the phas changes in the instrument transformers is to make the angle between th current and the potential in the wattmeter larger or smaller than that be tween the current and the e.m.f. of the circuit being measured.

If $\cos\theta$ = true power-factor and $\cos\theta_2$ = apparent power-factor (*i.e.*, power factor in the wattmeter obtained from the ratio of the watts and volt-ampere in the wattmeter), true watts = $(\cos\theta/\cos\theta_2) \times$ wattmeter reading. Th apparent power-factor, $\cos\theta_2 = \cos(\theta \pm \alpha \pm \beta \pm \gamma)$, where

θ = phase angle in main circuit,
α = equivalent phase angle in wattmeter,
β = equivalent phase angle in current transformers,
γ = equivalent phase angle in voltage transformers.

The angles α, β and γ are given positive (+) signs when they tend to de crease and negative (−) signs when they tend to increase the phase angl between the current and voltage in the instrument.†

180. Power-factor. The power-factor of a circuit is the ratio of the tru power in watts, as measured with a wattmeter, to the apparent power ob tained from the product of the current and the potential, in amperes an volts respectively. In the ordinary continuous-current circuits, the power factor is obviously unity but in rectifier circuits, for example, it may b slightly less than unity. In alternating-current circuits, the power factor is usually less than unity because the current and the potential ar not in phase. When the wave form is sinusoidal (and only then), the power factor is also equal to the cosine of the angle of lag.

181. The power-factor of single-phase circuits is obtained fro wattmeter, voltmeter and ammeter readings, by the relation $W/EI = co\theta$ where W = watts, E = volts and I = amperes.

182. The power-factor of polyphase circuits which are balanced i the same as that of the individual phases. When the phases are no balanced, the true power-factor is indeterminate. For all practica purposes, however, it is sufficiently correct to assume the power-factor to b that obtained by methods which give the average of the power-factors of th separate phases. In the **wattmeter-voltmeter-ammeter method,** th power-factor is, for a two-phase, three-wire circuit $W/\sqrt{2}$ (EI), (I i middle wire, E between outer wires) and for a three-phase, three-wire circui the power-factor is $W/\sqrt{3}$ (EI), wherein W = watts, E = volts and I amperes. In the **two-wattmeter** method, the power-factor of a two-phas three-wire circuit is obtained from the relation $W_2/W_1 = \tan\theta$, where W_1 the reading of a wattmeter connected in one phase in the same manner as single-phase circuit, and W_2 is the reading of a wattmeter connected with it current coil in the first phase, in series with the first wattmeter, and th potential coil across the second phase. Obviously, if the load is steady, on wattmeter is sufficient. If the phases are not balanced, the readings shoul be repeated with the instruments in the second phase, the true power-fact being taken as the average of the two results. In a **three-phase, three wire circuit,** the power-factor can be calculated from the readings of tw

* Bedell, F. "Direct and Alternating-current Testing." D. Van Nostran Company (1912), p. 228.

† Robinson, L. T. "Electrical Measurements in Circuits Requiring Curren and Potential Transformers." *Trans.* A. I. E. E., 1909, Vol. XXVIII, p. 100.

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wattmeters connected in the standard method for measuring power, as follows: $[(W_1 - W_2)/(W_1 + W_2)]\sqrt{3} = \tan\phi$, where W_1 is the larger reading, which is always positive, and W_2 is the smaller reading which may be either positive or negative.

183. Power-factor meters are instruments which indicate directly the power-factor of the circuit. Commercially there are two general classes, those involving the principle of **electrodynamometer wattmeters** and those based on the principle of **induction wattmeters.** The essential features of a Weston single-phase power-factor meter of the first class are shown in Fig. 69. It will be noted that the arrangement is similar to that in wattmeters, except that there are two coils, M, M^1, in the moving system instead of one. One coil, M, is connected across the line and in series with a resistance R, while the other coil, M^1, is connected in series with an inductance L. The current in the coil, M^1, will therefore be about 90 deg. out of phase with that in coil M. When the power-factor is unity, the reaction between the fixed coils, F, F^1, and the moving coil M will be a maximum while that between FF^1 and M^1 will be a minimum. The torque exerted on M will cause the moving system to take the position of minimum torque, that is, where the plane of M will be parallel to that of FF^1; the corresponding mark on the scale will therefore be 100. Similarly, at zero power-factor, coil M^1 will exert all of the torque and cause the moving system to take a position where the plane of M^1 will be parallel to that of FF^1; the corresponding indication is therefore zero. Theoretically, the indications will be **affected by the frequency,** because the current in L depends upon the frequency, but by proper design of the reactor, L, the effect of moderate variations in frequency can be eliminated.

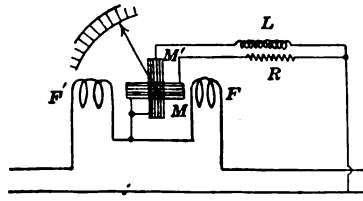


FIG. 69.—Diagram, Weston single-phase power-factor meter.

In the **polyphase meter,** Fig. 70 (for balanced circuits only), the inductance L is not required and the instrument is therefore entirely independent of the frequency. There are three coils in the moving system, one connected across each phase. The principle of operation is exactly the same as in the single-phase instrument, the moving system taking up a position where the resultant of the three torques will be a minimum, which position will vary with the average power-factor of the circuit.

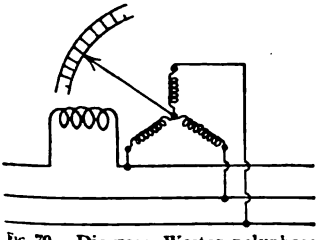


FIG. 70.—Diagram, Weston polyphase power-factor meter.

184. In Westinghouse power-factor meters, the dynamometer principle described in Par. **183** is used in some types. In others the induction principle is employed in the same manner that is applied in synchroscopes (Par. **289–291**).

185. General Electric power-factor meters employ the electrodynamometer principle (Par. **183**) in polyphase instruments. No single-phase instruments are made by this company.

ENERGY MEASUREMENTS

186. The practical unit of electrical energy is the **watt-hour,** which is the energy expended in 1 hr. when the power or rate of expenditure is 1 watt.

187. Energy is usually measured in watt-hours, with **watt-hour meters** (often incorrectly called integrating or recording meters). All watt-hour meters are, in reality, small motors in which the speed is propor-

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tional to the power and the revolving element operates a registering mec anism on which the energy consumption is recorded. Meters for co tinuous current are usually of the type which utilise the electrodynam principle of direct-current motors, while those for alternating curre utilize the principle of induction motors.

188. Continuous-current watt-hour meters. Continuous-currer meters may be divided into two classes, the **commutator type** and t **mercury motor type.**

189. Commutator-type meters are similar in principle to shunt moto The essential features are shown in Fig. 71. The moving element consis of an armature, *a*, a commutator, *c*, a a light metal disc, *d*, all mounted on steel shaft which rotates in a jew bearing. The armature is connect to the external circuit by means of ve light silver-tipped brushes. In seri with the armature is a light-load co pensation coil, *s*, and a resistance, *r*. The field coils are indicated at *f*, *f*.

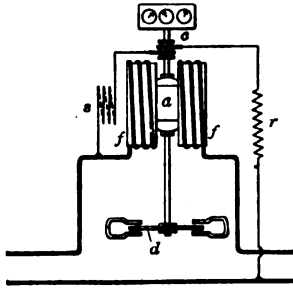


FIG. 71.—Diagram, commutator-type watt-hour meter.

190. Characteristics of commu tator-type meters. The essenti differences between this type of wat hour meter and a two-pole shunt mot are as follows: (a) entire absence iron in the magnetic circuits; (b) t armature element is connected acro the circuit and carries a very sm current, while the field element is series with the circuit and carries t main current; (c) the speed increas as the field strength increases which opposite to the effect in a shunt moto

191. The principle of operation of commutator-type meters as follows. The torque is proportional to the current in the armature co and to the field strength. Since there is no iron in the magnetic circuit, t latter is always proportional to the field current, hence the torque is pr portional to the two currents (as in a dynamometer wattmeter). The cu rent in the armature being proportional to the line potential, and the fie current equal or proportional to the line current, the torque is proportion to the power. In order to make the speed proportional to the power, mechanical load must be provided, in which the counter-torque will be pr portional to the speed. This load usually takes the form of a circular dis *d* (Fig. 71) of thin copper or aluminum which revolves between the pol of one or more permanent horseshoe magnets, with poles very close togethe The eddy currents induced in the disc react with the permanent-magn field, producing a counter-torque which will always be proportional to t speed. As the load current increases, the torque of the motor element i creases and the speed increases, because there is practically no count e.m.f. in the armature, *s*. But as the speed increases, the counter-torqu of the disc or generator element also increases and a speed is finally reache where the two torques balance each other and the speed remains constan Thus, theoretically, the speed will always be proportional to the power in t circuit. Each revolution represents a definite amount of energy, and b connecting the shaft to a suitable recording mechanism similar to that o gas and water meters, the total energy consumed is automaticall registered.

192. Effects of friction and temperature in commutator-typ meters. In practice, certain conditions prevent the speed from bein always proportional to the load, the principal factors being friction an temperature. **Bearing friction** is reduced to a minimum by using polishe sapphire or diamond jewels, with either a polished cone-shape shaft-en or a steel ball. Thus the contact surface is reduced practically to a poin The weight is reduced by using hollow shafts and very light aluminum non-metallic frames for the armature windings. **Commutator frictio** is reduced to a minimum by making the commutator diameter small, an

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using round brushes so that contact is made practically at a point. The gears in the registering mechanism are made as light as possible. The effect of friction is smaller as the torque is increased; hence the **ratio of torque to weight** is made as large as possible by making the armature spherical, which gives the maximum torque for the minimum amount of wire (weight).

193. Compensation for friction in commutator-type meters. Friction cannot be entirely eliminated and its effect is marked at light load, necessitating the use of a **compensating device.** This usually consists of a few turns of fine wire on the field coil, which are connected in series with the potential circuit. These turns are wound in a separate coil and the amount of compensation can be adjusted for each meter individually either by altering the position of the coil with respect to the field coils, as in General Electric and Westinghouse meters, or by changing the number of turns as in Columbia and Duncan meters.

194. Compensation for temperature in commutator-type meters. Temperature affects the performance of meters by: (a) changing the resistance of potential circuit; (b) changing the resistance of the drag disc; and (c) changing the strength of the permanent magnets. These changes produce a combined or resultant effect, which is compensated for by using for the series resistance in the potential circuit, one or more materials so combined that the final temperature coefficient of resistance counteracts the other effects when the air temperature changes.

195. The mercury-motor-type meter is most prominently represented by the direct-current meter made by the Sangamo Electric Company. Fig. 72 shows diagrammatically the circuits and scheme of operation. *D* is a solid copper disc floating in mercury *F* a float which supports the shaft and eliminates a jewel bearing; *H* is a laminated iron core and *C* is a chamber filled with mercury. The flux produced in the core, *H*, by the shunt coil, traverses the disc at two points which are diametrically opposite. The line current passes from *L* to L_1 through the mercury and diametrically through the disc. This disc being cut by flux, a torque is produced which is proportional to the current and the e.m.f.

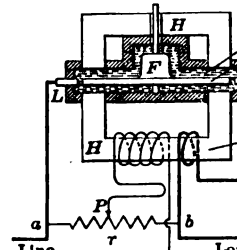


FIG. 72.—Diagram, Sangamo mercury-motor-type watt-hour meter.

196. Compensation for friction in mercury-motor-type meter. The friction due to the disc rotating in the mercury is **compensated in two ways.** One method is shown in Fig. 72. A high resistance, *r*, is connected in shunt with the armature, *D*, and the e.m.f. circuit is completed by the sliding contact, *P*. When the slider is at *b*, practically all of the shunt current will pass through *D* because of the resistance, *r*, thus adding to the torque. When the slider is at *a*, practically none of the e.m.f.-coil current will traverse the armature. In the second method, a circuit consisting of two wires of dissimilar metals, which form a thermocouple, is connected in parallel with the mercury chamber terminals, *L*, L_1. This couple is surrounded with a heating coil connected in series with the potential circuit. The e.m.f. produced by the couple causes current to flow through the disc thus producing the necessary torque to overcome the effect of friction at light load. The **increased mercury friction at high speed** is compensated by a series turn (or half a turn), *t*, on the core H. The drag or counter-torque is obtained with a separate disc and permanent magnets (not shown) in the usual manner.

197. Speed adjustments. The speed at all loads is equally affected by shifting the drag magnets diametrically with respect to the meter shaft, thus altering the retarding torque. This torque is a minimum with the magnets close to the shaft and a maximum with magnets near the edge of the disc. The speed at light load is adjusted independently as indicated in Par. 193.

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198. Typical Data Applying to Modern 110-Volt, 5-amp. or 10 amp., Direct-current Watthour Meters *

	G. E. Co. C-6, 5 amps.	Westinghouse CW-6, 5 amps.	Sangamo D, 10 amps.	Duncan E, 5 amps.	Columbia D, 10 amps.
Speed, full load, r.p.m.	46	41.7	25	36.7	3(
Torque, full load, mm.-grm.	170	140	55	180	9(
Weight, moving element, grm.	97	80	31‡	130	9(
Ratio, torque to weight	1.75	1.75	18	1.39	1.(
Drop, current circuit, volts at rated current.	1.15	1.0	0.03	.....	0.5
Loss, current circuit, watts at rated current.	5.75	5.0	0.3	.....	5.!
Loss, potential circuit, watts at 110 volts.	5.1	4.5	5.0	5.0	2.(
Resistance, armature, ohms	825	1,185	1,850§	.....	2,66
Resistance, compensating coil, ohms	65	315	.....	.....	45
Resistance, series resistance, ohms	1,540	800	450	.....	3,00
Resistance, potential circuit, total ohms	2,430	2,300	2,300	.....	6,11
Ampere-turns, field	300	600	.....	910	70
Ampere-turns, armature	800	1,500	.....	.....	2,10

199. Three-wire circuits are metered with two, two-wire meters o the kind described (Par. **188** to Par. **198**), **or a three-wire meter.** Th latter which is usually made in the **commutator type,** is the same as th two-wire meter except that the two field coils (which should be alike) ar separated electrically, and one is connected in each outer wire in such a manne that their fields are cumulative as before. When the load is exactly balanced the conditions are obviously the same as in a two-wire meter, and whe unbalanced the two field strengths add together so that the speed is pr portional to the total current.†

200. The metering of heavy-current circuits by means of standar meters becomes troublesome because of the large conductors required in th fields. While such meters have been made in capacities up to 20,000 amp they are very costly and not satisfactory at light loads. Watthour mete have been developed by some manufacturers, along standard lines, for ope ation with shunts. In order to develop sufficient torque without an exce sive shunt loss, it is necessary to employ shunts having small drop, large fie coils on the meters and relatively large leads from meter to shunt. Whe the meter has to be some distance from the shunt, the leads may have to b nearly as large as the wires in the main circuit, in order to keep down th resistance.

Another way to avoid the use of large meters is to connect severa smaller meters in parallel. Care should be taken to make the resistanc of the several branches equal, if the meters are of the same capacity; or, i the meters are of different capacities, inversely proportional to the capac ties of the meters. This will insure that none of the meters are overloade

201. Alternating-current watt-hour meters. Alternating-curren energy is almost always measured with induction type meters. Com mutator meters are seldom used on alternating-current circuits for the ver practical reason that induction meters are not only **more accurate,** bu much **less expensive** in first cost and in maintenance.

* From Electrical Meterman's Handbook, N. E. L. A., 1912, to whic readers are referred for further data. See also Fitch, T. T. and Huber, C. "A Comparative Study of American Direct-current Watthour Meters. Bureau of Standards Bulletin, 1913, Vol. X, p. 161. (Reprint No. 207.)

† The Sangamo Co. has recently developed a three-wire mercury meter (se Par. **195**).

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202. Induction-type watt-hour meters operate on the principle of the rotating magnetic field of the induction motor. The essential features of the principal makes of watt-hour meters are shown in the diagrammatic sketch, Fig. 73. *P* is the potential coil; *S* the series coil, and *C* a compensating coil. A metallic disc is free to revolve between the poles. The alternating magnetic fluxes from these poles will establish currents in the disc about as indicated by the arrows in the sketch at the right, which shows a portion of the disc and the poles. The potential winding, *P*, has many turns and is therefore highly inductive, while the series winding, *S*, is practically non-inductive; thus the fluxes produced by these two circuits are practically 90 time-degrees apart. Each flux is in phase with the current which produces it; and the e.m.f. generated in the disc, which is cut by the flux, is in time quadrature with the generating flux. Therefore, if it is assumed that the fluxes due to *P* and *S*, respectively, are in quadrature, the eddy currents produced by *P* will be a maximum at the same instant that the flux from *S* is a maximum, and *vice versa*. Thus a torque will be produced which is proportional to the instantaneous product of the eddy currents in the disc and the flux from the pole under which the current is flowing. This torque is proportional to the power used in the load circuit providing the time-phase difference of the currents in coils *P* and *S* is exactly 90 deg. at unity power-factor. The necessary retarding action or counter-torque is obtained with permanent magnets on this same disc as described under direct-current meters (Par. **191**).

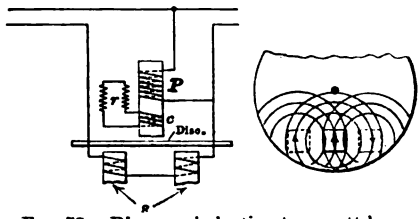


FIG. 73.—Diagram, induction-type watt-hour meter.

203. Compensating coil on induction-type meters. If the phase quadrature is not exact (Par. **202**), the meter will obviously not register correctly under any condition. In consequence of the ohmic resistance of the potential circuit, the current is never exactly 90 deg. behind the impressed e.m.f. At any instant, the flux E_f (Fig. 74) from the potential pole, instead of being in phase with the eddy currents, I_e, due to the line current, is slightly behind, as indicated. The torque is therefore proportional to the product I_e and oa, instead of I_e and E_{ff}. The meter will therefore run slow, but as a practical matter the error is so small that at unity power-factor it is insignificant. The error rapidly becomes large, however, as the power-factor decreases. As practically all alternating-current circuits have a power-factor less than unity, a **compensating coil** is used to eliminate the error. This coil is a short-circuited coil placed on the potential pole (see Fig. 73) and in which a current is induced 90 deg. behind the generating (potential) flux. Its flux, S_f, will be in phase with that (induced) current and therefore 90 deg. from E_f, with which it will combine. By adjusting the value of the resistance (lag adjustment) *r* (Fig. 73) the resultant flux can be brought into exact phase with I_e and the meter will then register correctly on all power-factors. It is evident that with lagging power-factor in the circuit, a meter will be slow if "under-lagged" and fast if "over-lagged." The opposite results will occur with a leading power-factor.

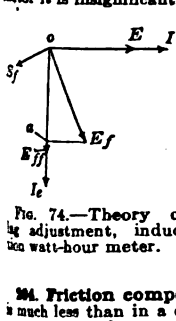


FIG. 74.—Theory of lag adjustment, induction watt-hour meter.

204. Friction compensation. The friction in an induction-type meter is much less than in a commutator-type meter because of the absence of a commutator and an armature. On the other hand, the torque is less (compare tables of characteristic data, Par. **198** and Par. **206**) and the effect of friction at light load has to be compensated. The principle employed in

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practically all meters is that in which a flux is produced at the potenti pole face, slightly out of phase with the main flux. Thus eddy currents w be produced in the disc which will be in phase with a small component of tl main flux, giving rise to a slight torque which can be made sufficient to ove come the friction torque. This "out-of-phase" flux is produced in vario ways in different meters. A common method is to place a short-circuite copper circuit or thin copper punching ("shading strip") in the potentia pole air-gap, in an unsymmetrical position, so that the desired unbalance flux will be obtained. In the Columbia meter, the effect is accomplishe by unbalancing the flux of the two potential poles by means of magnet shunts.

205. Adjustments of induction-type meters. Facilities are usual provided for conveniently adjusting the meter accuracy at light and full loa The position of the light-load compensation coil can be changed wi conveniently located screws, and the light-load speed thus altered. Spee adjustment at all loads is obtained by shifting the drag magnets wi respect to the axis, as in direct-current meters, or by shunting the flu by means of a movable soft-iron **keeper** bridging the air gap. Th power-factor or lag adjustment is made at the factory and if properly do should never require readjustment.

206. Typical Data Applying to Modern 110-volt Single-phase 6(cycle, 5-amp. Induction-type Watt-hour Meters*

	G. E. Co. I–10	Westing-house 0–A	Fort Wayne K–4	San-gamo H	Duncan M	Colum bia C
Speed, full load, r. p. m.	36	25	36.7	40	36.7	30
Torque, full load, mm.-grams	46.6	36	45	40	115	80
Weight, moving ele-ment, grams	26.3	15	21	15.6	46	30
Ratio torque to weight	1.77	2.32	2.14	2.5	2.5	2.6(
Drop, current circuit volts at 5 amp.	.....	0.3	0.12	0.1	.....	0.1
Loss, current circuit, watts at 5 amp.	0.98	0.75	0.59	0.5	.....	0.5
Loss, potential cir-cuit, watts at 110 volts	2.5	1.6	1.75	1.85	1.25	1.5
Power-factor, poten-tial circuit, per cent	.....	18	17	35	.....	70

207. Measurement of energy in alternating-current circuit The energy consumption in alternating-current circuits is measured wit watt-hour meters connected in exactly the same manner as are wattmeter for the measurement of power. (See Figs. 60 to 68.) In **three-wire, two phase** or **three-phase systems, polyphase meters** may be used. Suc meters comprise merely two single-phase meters in one case, with a commo shaft, and connected to the main circuit in the same manner as two singl phase meters.

Four-wire systems, unless balanced, require **three single-phas meters.** A **three-phase system** with a **grounded neutral** should b considered a four-wire system requiring three meters, unless it is completel balanced.

208. The total energy in a three-phase circuit is the algebraic sum of the indications of two single-phase meters, just as the total power i the algebraic sum of the readings of two wattmeters (Par. **174**). If **polyphase meter** is used, the summation is automatically performed, an

* From "Electrical Meterman's Handbook," N. E. L. A., 1912, to which th reader is referred for further data.

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when one element tends to run backward (power-factor less than 50 per cent.), it simply reduces the torque of the other one, so that the actual speed is still proportional to the net power in the circuit.

209. Polyphase meter connections. Obviously it is extremely important that the various circuits of a polyphase meter are properly connected. If, for example, the current-coil connections are interchanged and the line power-factor is 50 per cent., the meter will run at the normal 100 per cent. power-factor speed, thus giving an error of 100 per cent.

A **test for correct connections** is as follows: If the line power-factor is over 50 per cent., rotation will always be forward when the potential or the current circuit of either element is disconnected, but in one case the speed will be less than in the other. If the power-factor is less than 50 per cent. the rotation in one case will be backward.

When it is not known whether the power-factor is less or greater than 50 per cent., this may be determined by disconnecting one element and noting the speed. Then change the potential connection from the middle wire to the other outside wire and again note the speed. If the power-factor is over 50 per cent., the speed will be different in the two cases, but in the same direction. If the power-factor is less than 50 per cent., the rotation will be in opposite directions in the two cases.

210. Use of instrument transformers with watt-hour meters. When the capacity of the circuit is over 200 amp. series-type instrument transformers are generally used to step-down the current to 5 amp. If the potential is over 440 volts, series transformers are almost invariably used, irrespective of the magnitude of current, in order to insulate the meter from the line; in such cases, shunt-type transformers are also used to reduce the voltage to 110 volts. The **ratio and phase-angle errors** of these transformers (Par. **79** and Par. **104**) should be taken into account where high accuracy is important, as in the case of a large installation. These errors can be largely compensated for by adjusting the meter speed. The per cent. error corresponding to various phase angles is given in Par. **179**.

211. The accuracy of a watt-hour meter is the percentage of the total energy passed through a meter which is registered by the dials. The watt-hours indicated by the meter in a given time are noted, while the actual watts are simultaneously measured with standard instruments. On account of the time required to get an accurate reading from the register, it is customary to count revolutions of the rotating element instead of the register. The accuracy of the gear ratio between the rotating element and the first dial of the register can be determined by count. Since the energy represented by one revolution, or the **watt-hour constant**, has been assigned by the manufacturer and marked on the meter, the indicated watt-hours will be $K_h \times R$, where K_h = watt-hour constant and R = the number of revolutions. (See Testing Formulæ, Par. **222**.)

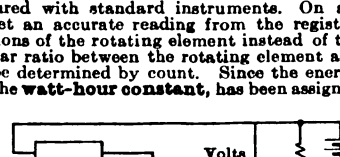


FIG. 75.—Connections for testing watt-hour meters—separate circuits.

212. Laboratory tests. Obviously the source of energy for meter testing should be as steady as possible. Storage batteries are largely used for direct-current meters; and special alternators, whose speed can be controlled, are used for alternating-current meters. The testing load may be banks of lamps, to which the meter and standard instruments are connected.

A better method is to separate the current and the potential circuits and connect them to independent sources, the former being a relatively large-current, low-voltage source and the latter a high-voltage, low-current source. Conditions are more easily adjusted by this method and in large meters a saving of energy is effected.

Where separate sources are used for the current and the potential coils, carbon rheostats are convenient for adjusting the current, and high-resistance rheostats connected "potentiometer" style are convenient for controlling

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the voltage, as indicated in Fig. 75. Resistance in the potential circuit of alternating-current meters will alter the quadrature phase relation, and therefore voltage regulation should be obtained with a variable ratio auto-transformer, an induction regulator or by field control.

213. Power-factor variation, in meter testing, can be obtained by several methods. In the **two-alternator** method, two generators are mounted on a common base, with a common shaft. The stationary members (armature or field) are made movable about the shaft with respect to the base and to each other. Thus with the potential coil of the meter connected to one machine, and the current coil to the other, any phase relation can be obtained by adjusting one movable member with respect to the other.

In the **transformer** method, a transformer with a large number of steps or a variable-ratio auto-transformer, is connected across one phase of a polyphase circuit and the potential coil of the meter is connected in such a manner that any phase relation can be obtained. Thus, referring to Fig. 76, the current coil of the meter is connected in series with conductor *a* of a three-phase circuit, and the potential coil is connected to *o* and to *p*, the latter being a tap on a transformer connected across phase *bc*. It is apparent that **any phase angle** between the current and the potential can be obtained in a range from 0 deg. to 60 deg. by moving the connection point *c* along the transformer winding. Angles from 60 deg. to 90 deg. lead or lag, can be obtained by changing the transformer to either of the other two phases and the meter connection from *o* to *x* or *y*. These changes can be instantly made with suitable switching arrangements. A similar arrangement can be made for a two-phase circuit, Fig. 77. It is also convenient to introduce such a transformer between the taps *o*, *p* and the meter, for the purpose of compensating for the variations in the voltage between *o* and *p*, and keeping the voltage constant at the meter. Two variable-ratio auto-transformers arranged in this manner make a convenient **phase shifter.**

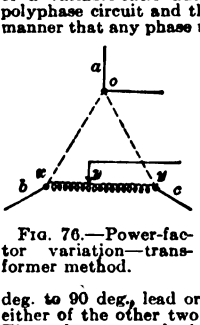


FIG. 76.—Power-factor variation—transformer method.

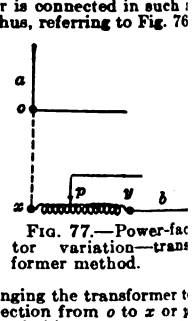


FIG. 77.—Power-factor variation—transformer method.

In the **reactance-coil** method, a reactance coil is introduced in the current circuit, the reactance being varied by moving an iron core in and out of the coil. It is difficult to obtain low power-factors with this method unless a separate low-potential current circuit is used, and then there is danger of **wave-form distortion.**

214. Measurement of meter torque. The torque is measured under normal conditions at full load by measuring the force in grams exerted at the edge of the disc, or at the end of an arm attached to the shaft. This force may be measured by means of weights, a calibrated watch spring, or by utilising the principle of the pendulum.* By measuring the radius of the disc or the arm in millimeters, the torque is obtained in millimeter-grams the usual unit.

215. Measurement of watt-hour meter losses. The losses in the windings of c.c. meters are calculated from the resistances, as determined with continuous current by standard methods. The losses in alternating-current meters are measured directly with wattmeters, but great care is required because of the very small amount of power and the small power-factor.

216. The standards for direct-current meter tests may be ammeters and voltmeters, in portable or special laboratory types, or potentiometers. In alternating-current meter tests, use is made of indicating wattmeters. The time in measuring the meter speed is usually determined with stop watches, reading to tenths of seconds. Where a large number of meters

* Agnew, P. G. Bureau of Standards Bulletin, 1911, Vol. VII, No. (Reprint No. 145.)

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are being adjusted, it is customary to use standardized or master watt-hour meters and thus eliminate the measurement of time and watts.

217. Service tests of watt-hour meters. There are two general methods of making tests on meters where they are installed: (a) with indicating instruments and a stop-watch and (b) with standard watt-hour meters (Par. 218).

In the **indicating-instrument method**, the time of a given number of revolutions at a known load is duly noted. The load on direct-current meters is measured with an ammeter and a voltmeter. In a modified form of this method, the load is an accurately standardized resistance and only a voltmeter is required, the watts being $W = E^2/R$, where W = watts, E = volt and R = ohms resistance of load. In the case of alternating-current meters, the load is preferably measured with a wattmeter.

218. The rotating-standard method of watt-hour meter testing is the most used, because only one observer is required and it is more accurate with fluctuating loads. **Rotating standards** are watt-hour meters similar to standard house-type service meters, except that they are made with extra care, are usually provided with more than one current and one potential range, and are more portable. A pointer, attached directly to the shaft, moves over a dial divided into 100 parts, so that fractions of a revolution are easily read. This standard meter is used by connecting it in series with the meter to be tested; the accuracy of the latter is determined by the "switch" method or the "eye-and-ear" method.

In the "switch" method the register only (in direct-current standards), or the entire moving element (in alternating-current standards), is started at the beginning of a revolution of the meter under test, by means of a suitable switch, and stopped at the end of a given number of revolutions. The accuracy is determined by direct comparison of the number of whole revolutions of the meter under test with the whole revolutions, and a fraction, of the standard.

In the "eye and ear" method, the number of whole revolutions of the standard is compared with a whole number of revolutions, and a fraction, of the meter under test. The revolutions of the standard are counted by ear by means of a telephone receiver and an electrical contact on the shaft, while those of the test meter are observed by eye.

219. A Wheatstone-bridge method for testing large watt-hour meters which cannot be conveniently cut out of service, and are on a load which fluctuates excessively, such as a railway load, has been developed by Messrs. Ingalls and Cowles.* The connections are shown in Fig. 78, where a and b are two fixed standard resistances or shunts, forming two arms of the bridge. The third arm is shown at c. A rotating standard with an adjustable fixed resistance d and a carbon rheostat e constitute the fourth arm. When e is adjusted until the portable galvanometer shows zero deflection, the ratio of watts passing through the two meters is $a/(a+b)$.

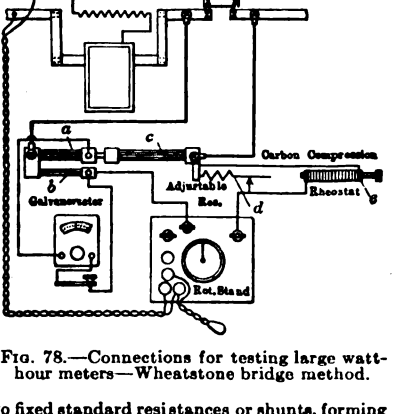


FIG. 78.—Connections for testing large watt-hour meters—Wheatstone bridge method.

*Ingalls, C. H. and Cowles. J. W. "Wheatstone-bridge Rotating-standard Method of Testing Large-capacity Watthour Meters;" *Trans.* A. I. E. E., 1912, Vol. XXXI, p. 1551.

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220. General precautions to be observed in testing watt-hour meter are as follows: (a) The test period should always be sufficiently long an a sufficiently large number of independent readings should be taken t insure the desired accuracy. In service tests, the period preferably shoul be not less than 30 sec. and the number of readings not less than three. I laboratory tests, 100-sec. periods and five readings are preferable. (I Capacity of the standards should be so chosen that readings will be taken reasonably high percentages of their capacity, in order to make observation or scale errors as small as possible. (c) Where indicating instruments a used on a fluctuating load, their average deflections should be estimated such a manner as to include the time of duration of each deflection, as well the magnitude. (d) Instruments should be so connected that neither th standards nor the meter being tested are measuring the potential-circuit lo of the other, that the same potential is impressed on both, and that the sam load current passes through both. (e) When the meter under test has n been previously in circuit, sufficient time should be allowed for the temper ture of the potential circuit to become constant, preferably not less than min.; this is important with direct-current meters, especially in the case rotating standards. In some types of the latter, special provision is made f rapid heating. (f) Guard against the effect of stray fields by locating th standards and arranging the temporary test wiring in a judicious manner.

221. Meter constants. The following definitions of various mete constants are taken from "Code for Electricity Meters."*

Register constant is the number by which the register readings must multiplied to obtain the registration. They are ordinarily used only large-capacity meters and are marked on the register.

Gear ratio is number of revolutions of the rotating element per revol tion of the first dial hand.

Watt-hour constant is the registration reduced to watt-hours per revol tion of the rotating element. It has a definite value for each type and rat capacity of meter.

Watt-second constant is the registration reduced to watt second per revolution of the rotating element. It is equal to watt-hour constan multiplied by 3,600.

Test constant is the constant assigned by the manufacturer for use the test formula for his meter.

222. Testing formulas. The accuracy of a watt-hour meter is the pe centage of the total energy passed through a meter which is registered on th dials. Accuracy in per cent. = meter watt-hours × 100/true watt-hours. Th value of one revolution having been assigned by the manufacturer, the met watt-hours = $K_h \times R$, where K_h = watt-hours per revolution or watt-hour co stant and R = revolutions in S seconds. The corresponding power in wat is $P = (3{,}600 \times R \times K_h)/S$ = meter watts and 100 × meter watts/actual watts per cent. accuracy. This is the standard formula for watt-hour meters.

223. Manufacturers' formulas for meter watts. When the te constant K differs from the watt-hour constant, K_h, the formula is chang accordingly as follows:

Manufacturer	K in terms of K_h	Manufacturers' formula for meter watts
Columbia	$K = 3{,}600\ K_h$	$W = R \times K/S$
Duncan	$K = 60\ K_h$	$W = 60 \times R \times K/S$
Fort Wayne	$K = 36\ K_h$	$W = 100 \times R \times K/S$
General Electric	$K = K_h$	$W = 3{,}600 \times R \times K/S$
Sangamo	$K = 3{,}600\ K_h$	$W = R \times K/S$
Westinghouse	$K = 3{,}600\ K_h$	$W = R \times K/S$

K_h = watt-hour constant, K = test constant (marked on meter, usually disc), R = number of revolutions in S seconds, W = meter watts.

224. Average accuracy of watt-hour meters. The accuracy of meter varies with the load, but it is often desirable to assign a value for th

* "Code for Electricity Meters." A. E. I. C. and N. E. L. A., 1912 ed pp. 95 and 96.

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average accuracy for all loads. Such a value obviously must be based on an arbitrary rule. The "Code for Electricity Meters" recommends the following:* When feasible, test the meter at 10 per cent. and 100 per cent. capacity of meter and at the normal load. Multiply the accuracy at normal load by three, add (to this) the accuracies found at each of the other two loads and divide the sum by five. This result is to be taken as the average accuracy. The "normal load" shall be taken as the percentage of the total rating of the connected load indicated in the table in Par. **225**.

225. Table of Normal Loads of Watt-hour Meters†

Per cent. of connected load which is equal to the "normal load" in calculation of average accuracy (Par. **224**)

Residence and apartment lighting	25 per cent.
Elevator service	40 per cent.
Factories (individual drive) churches and offices	45 per cent.
Factories (shaft drive) theatres, clubs, entrances, hallways and general store lighting	60 per cent.
Saloons, restaurants, pumps, air compressors, ice machines and moving picture theatres	70 per cent.
Sign and window lighting and blowers	100 per cent.

226. Watt-hour meter specifications. Probably the most extensive and authoritative specifications for the performance, installation, testing and maintenance of watt-hour meters in the United States are those included in the "**Code for Electricity Meters**" prepared by the Electrical Testing Laboratories under the joint direction of the Meter Committees of the A. E. I. Co.'s and the N. E. L. A. It is the basis of the rules issued by most of those state public utility commissions which have adopted regulations covering the subject of electricity meters. While scientific accuracy and correct technical principles are the basis of the code, the commercial phase of meter practice is not neglected. It covers the entire field of representative American meter practice including definitions, standards, specifications for meters and auxiliary apparatus, installation tests and maintenance.

227. Ampere-hour meters measure only quantity, that is, coulombs or ampere-hours, and therefore where they are used in the measurement of electrical energy, the potential is assumed to remain constant at a "declared" value, and the meter is calibrated or adjusted accordingly. Meters of this type may be divided into two general classes: electrochemical (Par. **228**) and electromotor (Par. **231**).

228. Electrochemical ampere-hour meters are essentially voltameters, because the quantity is measured by the amount of chemical decomposition of a substance caused by the passage of all or a part of the load current. In the **Edison chemical meter**, now obsolete, two zinc plates were immersed in a jar containing a zinc sulphate solution and connected in parallel with a shunt which in turn was in series with the load. The energy consumption was obtained by measuring the decrease in weight of the anode (positive) plate; 1.224 grams represented one ampere-hour.

229. Modern types of electrochemical ampere-hour meters. The principal modern types utilize the electrolysis of either water or mercury. The **Bastian meter** is an example of the former in which the change of the length of a column of water, as it is decomposed, is a measure of the quantity of electricity. A little caustic soda is added to decrease the resistance and a layer of oil is floated on top of the water to prevent evaporation and facilitate reading. A scale at the side of the tube is calibrated to read kilowatt-hours according to a "declared" voltage.

The **Wright meter** is the principal example of the **mercury type.** Metallic mercury is carried into a mercurous nitrate solution from a platinum cup anode and deposited in a platinum cup cathode, from which it flows into a fine tube. The height of this column is a measure of the energy consumption, a graduated scale being placed at the side of the tube. The electrodes are connected in parallel with a shunt, so that only a small portion of the load current passes through the solution. Provision is made for

* Page 99, 1912 Edition.
† "Code for Electricity Meters;" A. E. I. C. and N. E. L. A.; 1912 ed., p. 101.

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easily emptying the mercury from the tube into the anode receptacle wh the former becomes filled. This type of meter has been highly develop and inherent errors due to variation in temperature, concentration of t solution, level of mercury, effect of vibration, etc., are largely eliminat in the latest forms.

230. The principal advantages of electrolytic-type ampere-ho instruments are their low first cost and their simplicity, which results low maintenance cost. These are important items to power compani serving very small customers, especially where the rates are low; and m outweigh the disadvantages, the principal among which are elimination the potential element and relatively low accuracy.

231. Electromotor ampere-hour meters are similar to **watt-ho** meters, except that the field is produced by permanent magnets instead electromagnets. The rotating element is geared to a register which is ca brated in watt-hours for a given assumed voltage. There are two gene types, the electromagnetic and the mercury flotation. The former not made or used very much in this country.

The **Chamberlain and Hookham meter** is an example of the electr magnetic type. It employs a flat (pan-cake) armature winding mounted an aluminum disc which also serves as the drag element. Connection is ma to the circuit through a commutator and brushes in the usual manner. Th armature is connected to a low-resistance shunt which is in series with t load.

The **mercury type** meter is well represented by the **Sangamo met** which is practically the same as the Sangamo direct-current watt-hour met (Par. **195**), the electromagnet being replaced by permanent magnets.

232. Maximum demand meters. Some methods of selling ener involve the maximum amount which is taken by the customer in any peri of a prescribed length, that is, the maximum deman Many types of meters for measuring this demand ha been developed but space permits only a brief descri tion of a few types.*

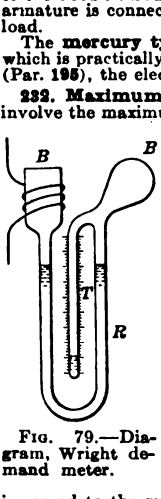


FIG. 79.—Diagram, Wright demand meter.

The **Wright demand meter** is a **time-lagg** thermal instrument. It consists of a hermetical sealed U-shaped glass tube (Fig. 79), partly filled wi a liquid. One leg *R* is connected near the top to smaller graduated tube *T*. Around the top of the tub *B*, is wound a resistance wire through which the curre flows. The resultant heating of the air forces the liqu up the tube *R* and, if sufficient, over into the graduat tube. The air heats up gradually and the necessa time lag is thus obtained. According to the makers, the overload continues 5 min., 80 per cent. of the lo will be indicated; 10 min., 95 per cent.; and 30 min. 1 per cent.

233. The General Electric Type W meter is **tim lagged.** It utilizes the principle of the induction wat hour meter. The torque of the moving element opposed by springs and a powerful drag on the dr disc. This arrangement provides the necessary tim lag. Two sweep-hands are provided on a dial. O is geared to the moving element, while the other is moved by the first o and left at the last position reached by it. This second pointer indicat therefore the maximum energy, until it is reset. **General Electric type** and **Westinghouse type RO** meters are also **time-lagged.**

234. Integrating demand meters measure an **integrated value** the quantity, usually kilowatt hours. In the **General Electric type meter** the kilowatt-hours indicated on a watt-hour meter are printed on paper tape at intervals of any desired length. The hourly intervals a also indicated. It is separately mounted and can be electrically connect to any standard make of watt-hour meter. The **Westinghouse type R** is similar in principle. The **General Electric type G meter** produces

* For a more complete discussion see Farmer, F. M.—"Electrical Mea urements in Practice," McGraw-Hill Book Co. 1917.

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continuous graphic record which shows at a glance the maximum of all the intervals during the day and when it occurred. **Type M meters** merely indicate the demand.

CURVE-DRAWING INSTRUMENTS

235. Curve-drawing or recording instruments are essentially indicating instruments so arranged that a permanent, continuous record of the indication is made on a chart. They are made for recording all electrical quantities that can be measured with indicating instruments: current, potential, power, frequency and power-factor. Here the fundamental principles are, in general, those of standard indicating instruments, with the addition of a suitable recording mechanism. The two general classes are those in which the record or chart is made directly by the moving element and those in which it is made by a separate mechanism. In all types the chart is driven by a clock mechanism which is entirely separate from the instrument proper.

236. Direct recording type. Examples of this class are Bristol, General Electric and Esterline meters. The distinguishing feature of the Bristol instrument is the use of a circular chart. The direct-current ammeters and voltmeters employ a stationary coil or solenoid, the moving element being a soft-iron armature working against flat springs. The alternating-current instruments employ the electrodynamometer principle, with one movable coil and one stationary coil. Suitable provision is made for multiplying the armature movement, and damping is obtained with a vane immersed in oil. These instruments are extremely simple and relatively inexpensive. The sensitiveness is seriously affected by pen friction and where high sensibility is essential, a smoked chart with a very light pointer is used instead of the usual paper chart with pen and ink.

The principle of General Electric alternating ammeters is shown in Fig. 80, where *AA* are fixed coils connected in series, and *B* is a soft-iron armature upon which the field acts and produces a torque, and which carries the pen. The chart is a continuous straight one, moving from 1 in. to 12 in. per hour, as desired. The record is made in the form of a straight line on rectangular coordinates. The pen in this instrument carries an ink-well and is self-inking.

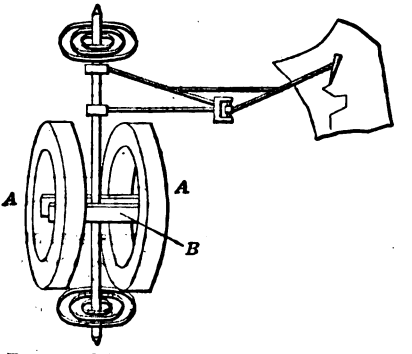


FIG. 80.—Diagram, G. E. alternating graphic ammeters.

Magnetic damping is employed. The voltmeters and wattmeters are similar except that they utilize the electrodynamometer principle, with fixed and moving coils. The greater friction and complication necessary to get the straight-line record necessitates a high torque and therefore a larger and more expensive construction.

Esterline direct-current instruments are of the D'Arsonval moving-coil type. The ammeters are 50-millivolt voltmeters connected to shunts. The alternating-current instruments are of the moving-coil or electrodynamometer type. The record is a straight-line one, made with a pen inked by siphon action from a stationary well. These instruments are made in portable as well as in switchboard form.

237. Where pen friction is particularly objectionable, as in low-reading millivoltmeters, the indicator is so arranged that it is in contact with the chart for only an instant at a time. In one form of Bristol instruments, a lever presses the end of the pointer against a smoked chart once

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a minute, the pointer being perfectly free in the interim. The record therefore a succession of dots. In other types of instruments, an inke thread or ribbon is interposed between the pointer and the paper chart.

238. The Westinghouse recording instruments are the principa example, in American practice, the class where the recordin mechanism is separate from th instrument proper. The movin element, by means of contact operates a relay which in tur operates the recording mecha ism. Thus the moving elemer does not have to produce a lar torque, while ample power can b applied to the recording mecha ism, and hence friction does no affect the sensitiveness of th instrument. The direct-currer instruments employ the D'Arsor val principle, using two sets of coi and magnets, astatically arrange The alternating-current instru ments use the principle of th Kelvin balance. Fig. 81 shows the scheme as employed in a voltmeter.

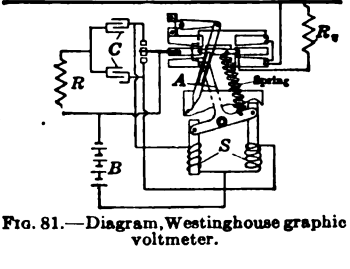


FIG. 81.—Diagram, Westinghouse graphic voltmeter.

239. The Callender recorder made by the Cambridge Scientific Instru ment Co. employs the princi ple of a slide-wire bridge (Fig. 82) in which the resistance of one arm, X, varies with the current, potential or power to be measured. As soon as the bridge is unbalanced, a D'Ar sonval galvanometer operates a relay, r or r', which moves a contact, c, along the slide wire s, until balance is restored, when the relay circuit opens. This contact also carries the record ing pen, which leaves an ink record on a rectilinear chart.

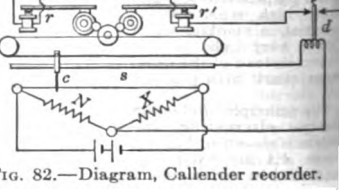


FIG. 82.—Diagram, Callender recorder.

INDUCTANCE MEASUREMENTS

240. General. The self-inductance, or coefficient of self-induc tion, of a circuit is the constant by which the time-rate of change of th current in the circuit must be multiplied, to give the self-induced counte e.m.f. Similarly, the **mutual inductance** between two circuits is th constant by which the time-rate of change of current in either circuit mu be multiplied to give the e.m.f. thereby induced in the other circuit. Sel inductance and mutual inductance depend upon the shape and dimensior of the circuits, the number of turns and the nature of the surrounding mediun

241. Standards of inductance are usually simple coils of copper wi suitably mounted on a non-conducting, non-magnetic frame. The turn are held rigidly in place by shellac, paraffine or other insulating mediun Inductance standards are made in single units like standard resistances, o In combinations, with plug connections, like a subdivided condenser or resistance box. In the Ayrton-Perry **variable standard** there are two coi centric coils, one fixed and the other movable. When connected in seri these coils form a variable inductance, the value of which at any relativ position is read from a circular scale at the top. Additional range is secure by connecting sections of the two coils in series-parallel combinations b means of plugs.

242. Methods. The most commonly employed methods of measurin inductance are (a) Wheatstone-bridge methods, where the inductance determined by comparison with a known inductance or known capacitance and (b) impedance methods where the inductance is determined by calcula tion from measurements made with alternating current.

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246. In Wheatstone-bridge methods a varying current must be employed. The potential drops, with steady current, are proportional to the resistances, whereas with a varying current the drops are proportional to the inductance, because $e = L\partial i/\partial t$, where L = inductance and e = e.m.f. induced by the current varying at the rate $\partial i/\partial t$.

244. When the detector is an ordinary D'Arsonval galvanometer the current may be varied by simply opening and closing the battery circuit, the galvanometer circuit being left closed; or a **secohmmeter** may be employed which rapidly reverses the current going into the bridge and simultaneously rectifies the galvanometer current, so that the latter is used as in ordinary bridge measurements. The current may also be rapidly interrupted with an induction-coil interrupter with a telephone receiver as the detector.

245. A method in which a standard inductance is used is shown in Fig. 83. If a continuous current is used, the bridge is first balanced with a steady current by adjusting r_3 and r_4, and again balanced with transient currents (battery key opened and closed) by adjusting r_1 and r_2; the bridge is then rebalanced with steady current, and again for transient currents, the process being repeated until the bridge is perfectly balanced under both conditions. At complete balance $L = L_s r_2/r_1$; where L = inductance being measured, and L_s = standard inductance. L will be in the same units as L_s

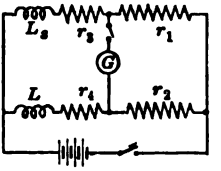


FIG. 83.—Inductance measurements with standard inductance.

246. Use of Vreeland oscillator. Small inductances, as well as large ones, may be measured with special convenience, accuracy and rapidity by this method (Par. **245**) if a source of high-frequency, sine-wave alternating current is available. A very satisfactory apparatus for this purpose is a Vreeland oscillator,* which delivers an absolutely pure sine-wave having a frequency which can be varied from a few hundred to about 2,000 cycles per second. It is operated from continuous current and is entirely static, the alternating current being derived from a circuit in which oscillations are set up by the rapid shifting of a mercury arc back and forth between two anodes. A telephone can be used as the detector, with a high degree of sensibility.

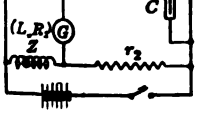


FIG. 84.—Inductance measurements with a condenser.

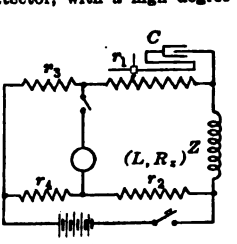


FIG. 85.—Inductance measurements with a condenser.

247. A method using a known capacitance is shown in Fig. 84. It is a modified form of **Maxwell's method** in which the condenser is connected in parallel with r_1, and two adjustments have to be made which are not independent of each other, one with steady currents and the other with transient currents. The two adjustments have to be repeated until complete balance is obtained. In Fig. 84 (**Rimington's method**), the bridge is balanced with steady current by adjusting r_3, and then with transient currents by varying r without changing the first adjustment. At balance,

$$L = \frac{Cr_3R_2}{r_1}10^{-6} \quad \text{(henrys)} \qquad (24)$$

* *Physical Review*, 1908, Vol. XXVIII, p. 286.

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where L = inductance of Z in henrys, r = ohms in parallel with C, C = capacitance of condenser in micro-farads, r_1 = total ohms of bridge arm to which condenser is connected and R_z = ohms of Z.

248. A similar method (Par. 247) is indicated in Fig. 85 in which the adjustments are independent of each other, the bridge being first balanced with a steady current and then with a transient current by adjusting r by shifting the condenser contact as in Fig. 84. At balance,

$$L = Cr^2 10^{-6} \quad \text{(henrys)} \qquad (25$$

where L = inductance of Z in henrys, C = capacitance of the condenser in micro-farads and r = ohms in parallel with C.

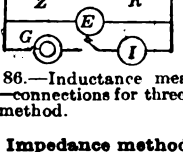


FIG. 86.—Inductance measurements—connections for three-voltmeter method.

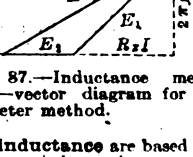


FIG. 87.—Inductance measurements—vector diagram for three volt-meter method.

249. Impedance methods of measuring inductance are based on the law of the impedance of a circuit carrying sine-wave alternating current and containing only inductance and resistance, that is,

$$Z = \frac{E}{I} = \sqrt{R^2 + (L2\pi f)^2} \text{ or } L = \sqrt{\frac{E^2 - I^2R^2}{(2\pi fI)^2}} \quad \text{(henrys)} \qquad (26$$

where L = inductance in henrys, E = drop in volts, I = current in amperes, R = resistance in ohms, and f = frequency in cycles per sec. Obviously due allowance should be made for the voltmeter current where its magnitude is sufficiently important.

250. In the three-voltmeter method, the inductance to be measured is connected in series with a non-inductive resistance as shown in Fig. 88.

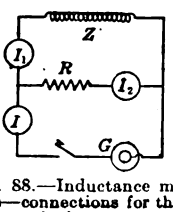


FIG. 88.—Inductance measurements—connections for three-ammeter method.

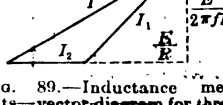


FIG. 89.—Inductance measurements—vector diagram for three-ammeter method.

The current, I, is measured, also the total volts, and the volts across the inductance Z and the resistance R. From these readings a triangle is constructed, Fig. 87. If R is known, the quantity $2\pi fLI$ can be calculated from the triangle. If R is unknown, $2\pi fLI$ can be obtained by graphical construction. I and f being known, L is obtained by calculation.

251. The three-ammeter method is similar. The connections are shown in Fig 88, and from the three currents, Fig. 89 is constructed. The e.m.f., E, can be measured directly or, if R is known, by calculation from the relation $E = RI_2$. Hence L can be obtained from the quantity $E/2\pi fI$.

252. In circuits containing iron the inductance varies with the frequency and with the current; hence alternating current of known frequency and intensity must be used. In such cases a bridge method with a standard inductance is convenient. A vibration galvanometer, a

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synchronous contactor or a separately excited electrodynamometer can be used as the detector. The bridge is first balanced for resistance (that is, balanced for bridge-arm drops in phase with the supply current) and then for inductance (bridge-arm drops 90 deg., from the phase of the supply current).

253. The mutual inductance, M, between two coils may be measured by several methods, as follows:

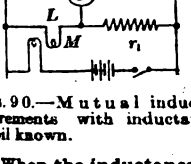


FIG. 90.—Mutual inductance measurements with inductance of one coil known.

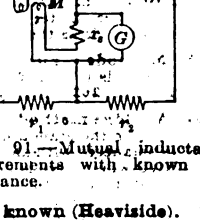


FIG. 91.—Mutual inductance measurements with known self inductance.

(a) **When the inductance, L, of one coil is known (Heaviside).** The connections are shown in Fig. 90. The bridge is balanced as in inductance measurements for both steady and transient currents. Then

$$M = \frac{-Lr_3}{(r_1+r_2)} \qquad (27)$$

M and L are in same units, r_1 and r_2 in ohms.

(b) **By comparison with a known self-inductance.** Connect as in Fig. 91. First balance for steady currents; then balance for transient currents by adjusting r_3. Then

$$M = -L\frac{r_1(r_s+r)}{(R+r_1)^2} \qquad (28)$$

where r = resistance of secondary of mutual inductance M, and R = resistance of self-inductance, L. M is in same units as L.

(c) **By comparison with a known capacitance.** Connected as in Fig. 92. Balance as before for steady and transient currents by adjusting r_1 and r_2. Then

$$M = Cr_1r_2 10^{-6} \quad \text{(henrys)} \qquad (29)$$

where M = mutual inductance in henrys, C = capacitance in microfarads, r_1 and r_2 in ohms.

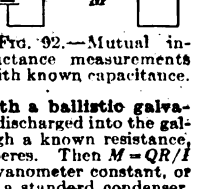


FIG. 92.—Mutual inductance measurements with known capacitance.

(d) **By connecting the secondary in series with a ballistic galvanometer** and noting the quantity, Q, in coulombs, discharged into the galvanometer when the primary circuit is closed through a known resistance, of R ohms, the steady value of the current being I amperes. Then $M = QR/I$ in henrys. The quantity is determined from the galvanometer constant, or more directly, by calibrating the galvanometer with a standard condenser.

CAPACITANCE MEASUREMENTS

254. General. The electrostatic capacitance of two conductors separated by a dielectric depends upon the surface area of the conductors, the distance between them, the character of the dielectric, the temperature and the pressure.

255. Condensers are groups of conductors separated by insulation and especially constructed to have a known capacitance. Commercial forms are generally made of sheets of tin foil separated by mica or paraffined paper, alternate layers of tin foil being connected to the same terminal. One box may contain one or more of these groups, with plug or other arrangements for connecting them in various series or parallel combinations.

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256. The capacitance of a group of condensers in series is

$$C = \frac{1}{\frac{1}{C_1}+\frac{1}{C_2}+\frac{1}{C_3}+\ldots\ldots\frac{1}{C_n}} \qquad (30)$$

When connected in parallel,

$$C = C_1+C_2+C_3+\ldots\ldots C_n \qquad (31)$$

257. In high-grade standard condensers, the aim is to reduce the absorption, the dielectric hysteresis and the ohmic losses to a minimum. **Commercial standards** are made with tin-foil and high-grade mica, bound together under high pressure. **Primary standards,** however, are made with air as the dielectric, in which absorption and leakage are nil.

258. Methods. Electrostatic capacitance measurements are made by bridge methods (Par. **259**), with a ballistic galvanometer (Par. **260**), by loss of charge (Par. **262**), and by impedance methods (Par. **263**).

259. A bridge method of measuring capacitance is shown in Fig. 93. The ratio, r_1/r_2, or the standard condenser (if adjustable), is adjusted until the bridge is balanced; with an ordinary D'Arsonval galvanometer this condition is indicated when there is no "kick" as the reversing switch is changed from one position to the other. If interrupted currents or high-frequency alternating currents are used, with a telephone receiver, balance is indicated by silence in the receiver. Then $C_2 = C_1 r_1/r_2$. The resistance should be non-inductive, anti-capacity and relatively large—several hundred ohms. Obviously, maximum sensitivity is obtained when C_2 and C_1 are about equal. By employing a Vreeland oscillator (Par. **246**) and an adjustable air or oil condenser, small capacitances can be very accurately measured by this method.

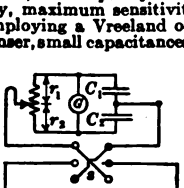


FIG. 93.—Capacitance measurements, bridge method.

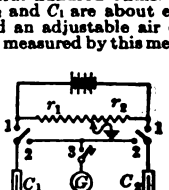


FIG. 94.—Capacitance measurements, method of mixtures.

260. In the ballistic galvanometer method, the deflection is noted when the unknown capacitance is discharged through it, immediately after having been charged at some known potential. A reading is then obtained with a standard condenser, the deflection being made about the same as before, by varying the capacitance or the charging potential. The capacitance can then be computed from the relation $d/d_1 = CE/C_1E_1$; where d, d_1, C, C_1, and E, E_1 are the respective deflections, capacitances and potentials. This method is best suited to relatively large capacitances, such as lead-covered, paper-insulated cables, etc.

261. The Thomson method of mixtures is shown in Fig. 94, where C_1 is a cable, transmission line or other capacitance to be measured, and C_2 is a standard condenser. First the switches are closed at 1, 1, and the condensers charged to potentials corresponding to r_1 and r_2 respectively. After complete charge (a cable may require several minutes), the switches are shifted to 2, 2 and the charges equalised. If, then, the switch at 3 is closed, the deflection of the galvanometer will be proportional to the difference of the charges. This operation is repeated with various ratios r_1/r_2 until there is no deflection. Then $C_1 = C_2 r_1/r_2$.

262. In the loss of charge method, Fig. 95, the condenser to be measured is first completely charged by moving switch b to a, and then immediately discharged through a ballistic galvanometer by moving b to c. The condenser is again charged and allowed to discharge through a known high

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resistance, R, a given number of seconds, t, before being connected to the galvanometer a second time. The capacitance in microfarads is

$$C = \frac{t}{R \log_{10} d_1/d_2\ 2.303} \quad \text{(microfarads)} \quad (32)$$

where d_1 = first deflection, d_2 = second deflection and R = resistance in megohms. This method is applicable only where the resistance of the condenser being measured is very high, such as porcelain insulators.

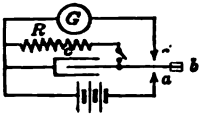


FIG. 95.—Capacitance measurements, loss of charge method.

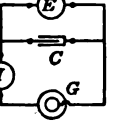


FIG. 96.—Capacitance measurements, impedance method.

263. In the impedance method, the capacitance is computed from the reactance as measured with an ammeter and a voltmeter, with alternating current of known frequency as shown in Fig. 96. Then

$$C = \frac{I}{2\pi fE}(10^6) \quad \text{(microfarads)} \quad (33)$$

where C = capacitance in microfarads, E = volts, I = amperes, and f = frequency in cycles per second. Unless the voltmeter is an electrostatic instrument it should be disconnected when taking current readings. With small capacitances where I is small, care should be taken that the high inductance of a low reading ammeter does not introduce an error. The capacity given by this method depends upon the wave form. Therefore the test should be made from the circuits to which the apparatus being measured will be connected in service. Obviously this method is correct only for a zero power-factor condenser.

264. The specific inductive capacity of a material is the ratio of the capacitance of a condenser with the material as a dielectric to that of the same condenser with air as a dielectric. The following substitution method is convenient for sheet material. An air condenser formed by two metal plates is set up and measured. Then several sheets are slipped into the air space and the measurement repeated. The spacing of the plates minus the thickness of the sheets gives the air space in the second measurement. From the capacitance of the latter (by calculation from first measurement or by Par. 266) the capacitance of the material is computed by formula 30. External capacitance can be determined by keeping one plate grounded and making an initial measurement with that plate removed.

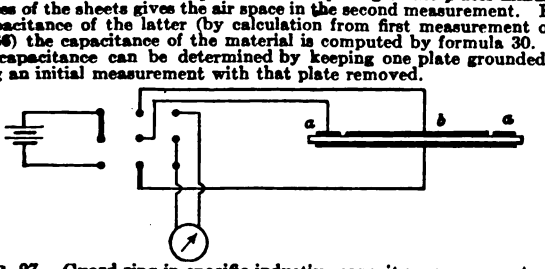


FIG. 97.—Guard ring in specific inductive capacity measurements.

265. The "fringe effect" (electrostatic field in the dielectric extending beyond the area corresponding to the electrodes) may be eliminated by using a guard ring, a, a, of tin-foil as shown in Fig. 97. It is very close to the electrode b and is so connected in the circuit that only the charge on b is measured.

266. The capacitance of an air condenser is $C = A/4\pi t \times 9 \times 10^5$, where C = capacity in microfarads, A = area in square centimeters and, t = thickness of layer of air in centimeters.

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WAVE-FORM MEASUREMENTS

267. Methods. The instantaneous variations of current and potentia in a circuit are measurable by step-by-step methods (Par. **268**), and with th oscillograph, (Par. **271**.) The former is applicable only where the current anc the potential are strictly periodic and recurrent, as in a normal alternating current circuit. The oscillograph can be used under all conditions, but is es pecially applicable to measurements of transient phenomena (Par. **268**), *such* as those which occur during switching operations on direct-current and al ternating-current circuits. Where the wave form is to be analyzed, the forme is the more convenient and accurate.

268. A convenient "step-by-step" arrangement is shown in Fig. 98. The contact device consists of two slip-rings and a four-part commutator One slip-ring is connected to one terminal of the source, the other to a volt meter, and the commutator to a condenser. By means of this arrangement the condenser after being charged is immediately discharged through the voltmeter. These impulses follow each other so rapidly that a steady de flection is obtained, and by suitable adjustment of R and r on continuous current, the voltmeter may be made direct reading. The instantaneous values at any point on the wave are obtained by shifting the brushes around the shaft. The switch is closed at 1 for voltage measurements and at 2 for current measurements.*

The General Electric **wave meter** operates on this principle. There are eight segments, four connected to each of two slip rings. There are two contact brushes so that two waves can be taken simultaneously. Suitable provision is made for tracing the wave form on a photographic plate.

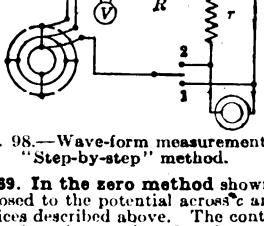


FIG. 98.—Wave-form measurements, "Step-by-step" method.

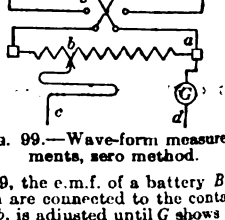


FIG. 99.—Wave-form measurements, zero method.

269. In the zero method shown in Fig. 99, the e.m.f. of a battery B is opposed to the potential across c and d, which are connected to the contact devices described above. The contact point, b, is adjusted until G shows no deflection; then the length ba is a measure of the e.m.f. G may be a portable galvanometer, or a telephone in conjunction with a slide wire and a contact stylus as used in the Sage ohmmeter (Par. **139**).

270. The form of a high-tension wave may be obtained by using the device in Par. **227**. The indication of the voltmeter is obtained at various positions of the brushes, from which the wave form may be plotted. An oscillograph (Par. **271**) may be utilized in conjunction with a specially designed current transformer.†

271. The oscillograph is a form of galvanometer in which the natural period of the moving system is so small that the deflections will always be proportional to the instantaneous value of the current flowing through the coil. The indicator is a beam of light from an arc lamp, reflected from an extremely small mirror attached to the moving system. The path of the beam is determined visually or photographically. Recurrent or periodic waves may be rendered stationary and therefore visible by suitable optical systems as indicated below. Transient phenomena must be photographed.

272. In the moving-iron type of oscillograph, first proposed by

* See also Frederick Bedell. "Condenser Current Method for the Determination of Alternating Wave Form," *Electrical World*, 1913, Vol. LXII, p. 378.

† Bennett, Edward, "A Milliampere Current Transformer," *Trans.* A. I. E. E., Vol. XXXIII, p. 571 (1914).

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Blondel,* a very small piece of soft iron is suspended in a strong magnetic field, thus forming a polarised magnet. Near this strip are placed two small coils, which carry the current to be investigated. Because of its very small period, this magnet will follow every variation in the current.

273. The moving-coil type of oscillograph developed by **Duddell** consists of a single-turn coil formed by passing a phosphor-bronze strip over a pulley suspended by a spring, and between the poles of a powerful electromagnet as shown in Fig. 100. It has a much lower inductance than the moving-iron type and therefore a wider range of application. This type is now in most general use and in this country is prominently represented by the General Electric oscillograph, a very simple, rugged and practical instrument. Three elements or vibrators are usually provided in the latter, and three waves may be taken simultaneously. The electromagnets are wound for 110 volts, at which excitation the sensibility of the vibrators is of the order of 0.005 amp. per millimeter deflection. The moving system is immersed in a well, with a glass front, and filled with oil to dampen the oscillations. The natural frequency is of the order of 5,000 vibrations per second.

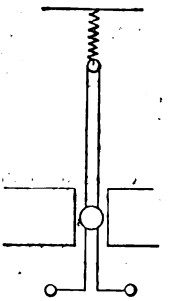


FIG. 100.—Element of moving coil type of oscillograph.

274. Various receiving devices are used to render the wave visible to the eye. One scheme employs a rotating mirror driven by a synchronous motor connected to the circuit being tested. In the General Electric oscillograph the beam of light from the arc, *a*, Fig. 101, is concentrated by a lens, *b*, upon the mirror, *l*, of the vibrator, which is oscillating about an axis perpendicular to the beam. The mirror, *m*, is driven by a cam, *d*, which gives a comparatively slow forward stroke and a quick backward stroke. When this mirror is stationary the image of the reflected beam at *s* is a straight line the length of which is proportional to twice the angular deflection of the vibrator. If the mirror is rotated forward, the image at *s* is spread out thus tracing a wave. The wave is made to appear stationary by automatically cutting off the light on the return stroke of *m* by means of the shutter *e*.

275. Permanent oscillograph records may be made by tracing the wave on transparent paper or tracing cloth placed on the screen, *s*, referred to above (Par. 274). For making photograph records, or oscillograms, the visual attachment is replaced by a light-proof cylinder containing the film and fitting over an opening in the oscillograph case through which the beam of light passes to the film. The film is unrolled from one spool on to another and past the opening by a motor-driven mechanism; its speed is adjusted to suit the conditions. In the case of transient phenomena it is often found necessary to arrange special devices to start the film automatically at the proper time in order to get the phenomena on the film. A record of elapsed time in direct-current phenomena can be obtained by connecting one of the elements to a source of alternating current of known frequency, or by means of an electrically driven tuning-fork of known frequency. A small mirror mounted on the end of one prong and so placed that it will reflect a part of the beam, will give an excellent time record. The scale of ordinates is obtained by calibration on continuous current, the deflection of the spot of light corresponding to a known current, or voltage, being noted.

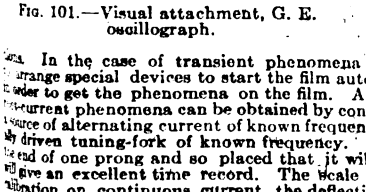


FIG. 101.—Visual attachment, G. E. oscillograph.

276. Standard wave form. It is desirable that commercial alternating-current wave forms be as near a sine curve as possible in order to

* Blondel, A. E. *Comptes Rendus*, 1893, Vol. CXVI, p. 502.

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reduce iron losses, excitation currents, charging currents, etc., to a minimum. The present A. I. E. E. standard method of measuring the deviation from a sine curve is simply to measure the greatest difference between corresponding ordinates at any point along the axis of abscissæ. In another method for determining wave form distortion which has been tentatively adopted by the A. I. E. E., the admittance of a carefully prescribed network of resistances and inductances is measured with the unknown wave form and compared with that for a sine wave.

277. In high-voltage testing it is particularly important that the value of the maximum instantaneous voltage be available, because the stress to which insulation is subjected depends upon this value. When the wave is distorted, the maximum value and the ratio of the maximum to mean-effective (amplitude or peak factor) have to be obtained from a plot of the wave. This may be taken with a wave meter or with an oscillograph, preferably connected to a test coil in the high-tension winding or to the secondary of a shunt-type instrument transformer connected to the high-tension circuit.

A method which can be used directly on the highest voltages* is indicated in Fig. 102, where C is a series of condensers connected across the high-tension circuit. The end condenser C_1 is grounded and connected in parallel with a commutator, R, driven by a synchronous motor. The bars on the commutator are very narrow and are one polar space apart, so that contact is practically instantaneous. The brushes are shifted until the voltmeter, V, indicates a maximum. The multiplying ratio is obtained from the ratio $(C+C_1)/C_1$. The instrument may be calibrated by noting the indication corresponding to the mean effective value, which is obtained with the motor stationary and the brushes resting on the bars. This indication is compared with a spark gap or other standard. The method assumes that the capacity of V is negligible in comparison with C_1. Obviously the condensers can be dispensed with by connecting directly to a test coil on the high-tension winding.

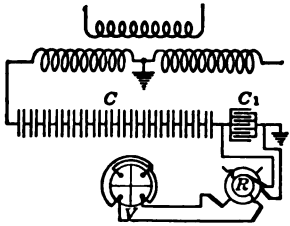


FIG. 102.—Wave meter for high voltage circuits.

Another method which is simpler has been developed by J. R. Craighead.† A thermionic electric valve (kenotron) is connected in series with a condenser and an electrostatic voltmeter is connected across the condenser. Measurements may be made directly on voltages up to 25,000 or 30,000 volts and indirectly up to any voltage where a voltage coil has been installed in the transformer.

FREQUENCY MEASUREMENTS

278. General. The frequency of an alternating current is $f = nr/2$, where f = frequency in cycles per second, n = number of poles, and r = revolutions per second. It may therefore be determined by measuring the speed of the generator supplying the circuit or the speed of a synchronous motor operated from the circuit.

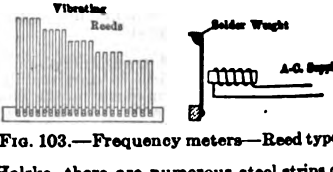


FIG. 103.—Frequency meters—Reed type.

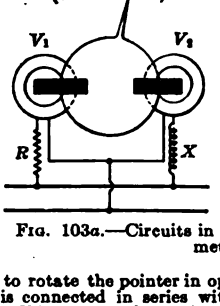
279. Frequency meters indicate the frequency directly. In the **reed type** as made by Hartman and Braun or Siemens and Halske, there are numerous steel strips of different lengths, each rigidly fastened at one end and free to vibrate at the other. The strips are placed in the field of an electromagnet which is ener-

* Sharp, C. H. and Farmer, F. M. "Measurements of Maximum Values in High-voltage Testing;" *Trans.* A. I. E. E., 1912, Vol. XXXI, p. 1617.

† Craighead, J. R., "Measurement of the Crest Value of Alternating Voltage by the Kenotron, Condenser and Voltmeter," *General Electric Review*, 1919, Vol. XXII, No. 2, p. 104.

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ined from the circuit to be measured, as shown in Fig. 103. The stripe have different natural periods, and the one with a period corresponding to the alternations of the magnetic field will be set in vibration. The ends are turned up and painted white so that the particular reed in a row, which is vibrating, will be indicated by a white band or blur. Each reed is carefully adjusted to an exact period by attaching minute weights. These meters are made in various ranges and with reeds adjusted from 0.25 cycle to 2 cycles apart.



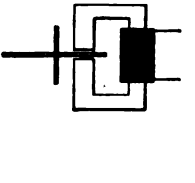


FIG. 103a.—Circuits in Westinghouse frequency meters.

280. The Westinghouse frequency meter consists of two voltmeter movements, mechanically so interconnected that they tend to rotate the pointer in opposite directions. A non-inductive resistance R is connected in series with one movement, V_1 (Fig. 103a) and an inductance X is connected in series with the other element, V_2. The apparent resistance of the inductive movement varies with the frequency and thus varies the amount of current taken by it. Therefore each frequency will cause the pointer to take up a different position.

281. The Weston frequency meter is shown in Fig. 104, where 1, 1 and 2, 2 are fixed coils, 90 deg. apart, and c, c is the movable element consisting of a simple, soft-iron core mounted on a shaft, with no control of any kind. One coil, 2, 2, is connected in series with a non-inductive resistance, R_2, and the other coil, 1, 1, in series with an inductance, X_1. A second non-inductive resistance R_1 is connected in parallel with 1, 1, and X_1. A

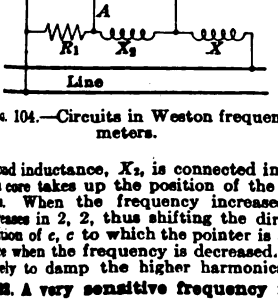


FIG. 104.—Circuits in Weston frequency meters.

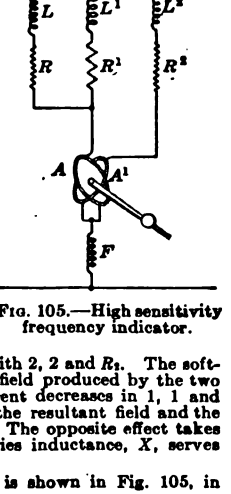


FIG. 105.—High sensitivity frequency indicator.

xtra inductance, X_2, is connected in parallel with 2, 2 and R_2. The soft-on core takes up the position of the resultant field produced by the two oils. When the frequency increases, the current decreases in 1, 1 and ncreases in 2, 2, thus shifting the direction of the resultant field and the osition of c, c to which the pointer is attached. The opposite effect takes lace when the frequency is decreased. The series inductance, X, serves erely to damp the higher harmonics.

282. A very sensitive frequency indicator is shown in Fig. 105, in

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which the principle of resonance (Sec. 2) in an electrical circuit is employed.* In a 60-cycle instrument, one main circuit is adjusted for resonance at about 70 cycles, another at about 58 cycles and the third circuit at about 36 cycles. The latter two are connected in parallel, and then in series with coil *A*; the first circuit is in series with coil A^1, both coils being in series with the field *F*. With the centre of a 6-in. (15 cm.) scale marked for 60 cycles, half-scale deflection is obtained for a variation of only 5 cycles either way.

SLIP MEASUREMENTS

283. General. The **slip** of a rotating alternating-current machine in per cent. is the difference between its speed and the synchronous speed, divided by the synchronous speed. It may be determined by noting the difference between the measured speed of the machine and the synchronous speed but direct methods are more accurate.

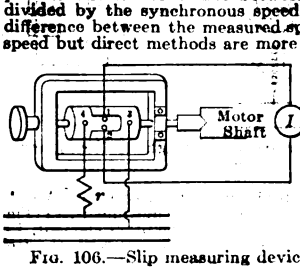


FIG. 106.—Slip measuring device.

Millivoltmeter method. If sufficient stray field is produced by the current in the secondary of an induction motor, a direct-current millivoltmeter connected to an adjacent coil of wire or across the motor shaft or frame will oscillate at slip frequency, each swing being one pole slip.

284. Dooley's method of measuring slip. One form of device for indicating the slip of an induction motor† is shown diagrammatically in Fig. 106. A small cylinder made of conducting material, and in two parts, each insulated from the other, is mounted in a frame. Four small brushes, 1, 2, 3, and 4, bear upon the cylinder as shown. The brushes, 3, 4, are connected through a resistance, *r*, across one phase of the supply circuit and the brushes, 1, 2, are connected to a low-reading continuous-current ammeter, *I*. Each time the brushes, 1, 2, bridge the insulating strip as the cylinder rotates, the circuit is completed in alternate directions through the ammeter. The cylinder should have as many segments as the motor has poles. The ammeter will indicate a constant current at synchronous speed, and an oscillating current for any speed above or below synchronism, because the impulses of current through the brushes, 1, 2, will occur at the same point on the wave at synchronous speed, and at constantly advancing or retarding points for other speeds. Thus, the ammeter will be reversed each time the motor loses one-half of a cycle, and will reach a maximum positive value each time the motor loses one complete cycle. If the motor loses *n* cycles per min., then the slip in per cent. $= 100n/60f$, where f = frequency of the system in cycles per sec.

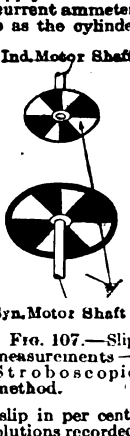


FIG. 107.—Slip measurements—Stroboscopic method.

285. Stroboscopic method. The device indicated in Fig. 107 does not require the measurement of frequency. A black disc with white sectors, equal in number to the number of poles of the induction motor, is attached with wax to the induction-motor shaft. It is observed through another disc having an equal number of sector-shaped slits and carried on the shaft of a small self-starting synchronous motor, in turn fitted with a revolution counter which can be thrown in and out of gear at will. If *n* is the number of passages of the sectors, then $100n/n_s n_r$ = slip in per cent. where n_s = the number of sectors, and n_r = the number of revolutions recorded by the counter during the interval of observation. For large values of slip the observations can be simplified by using only one sector ($n_s = 1$); then n = the slip in revolutions.

286. A direct-reading slip-measuring device is shown in Fig. 108.

* Pratt W. H. and Price D. R. "Resonant Circuit Frequency Indicator," *Trans.* A. I. E. E., 1912, Vol. XXXI, p. 1595.

† Dooley, C. R. *Elec. Club Journal*, 1904, Vol. I, p. 590.

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D is a carefully turned and hardened conical drum driven by the motor being tested, through a flexible shaft, *S*. The long screw, *H*, moves a carriage, *C*, parallel to the surface of *D*. This carriage carries a wheel *d*, also carefully turned and hardened, which has a line edge and is kept in contact at all times with the surface of *D* by means of a light spring. Thus it revolves with *D*. On the same shaft is a disc, *sd*, with alternate black and white sectors painted on it, the number of sectors being equal to the poles of the motor being tested. The diameter of *d* is made equal to that of the small end of *D*. At the setting corresponding to the small end of *D*, the scale along which the carriage moves is marked zero. This corresponds to synchronous speed. As the speed of *D* decreases, it is necessary to move *d* toward the large end of *D* in order to keep the speed of *d* the same as at synchronous speed. This distance is a measure of the slip. The synchronous speed of *sd* is indicated when it appears to stand still, when illuminated by an arc lamp connected to the same circuit to which the motor is connected. Thus, if *D* is 2 in. (5.1 cm.) in diameter at the small end, 2.5 in. (6.35 cm.) at the large end and 5 in. (12.7 cm.) long, slips from 0 to 20 per cent. can be measured with a precision within 0.2 per cent. A more sensitive detector consists of a commutator in place of *sd*, connected in series with a direct-current voltmeter and the circuit to which the motor is connected. The indication is a maximum at synchronous speed.

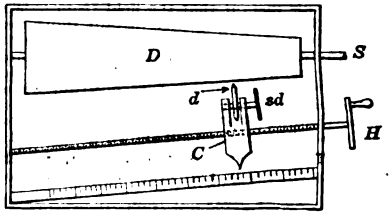


FIG. 108.—Slip measuring device.

287. Synchronism indicators. In order to connect any synchronous machine in parallel with another machine or system, the two voltages must be made equal and the machine must be synchronized, that is, the speed so adjusted that corresponding instantaneous values on the two waves are reached at the same instant, when they will be in exact phase. Furthermore, with polyphase machines, the direction of phase rotation must assuredly be the same. This, however, is usually made right once for all when the machines are installed, the phases being so connected to the switches that the phase rotation will always be correct.

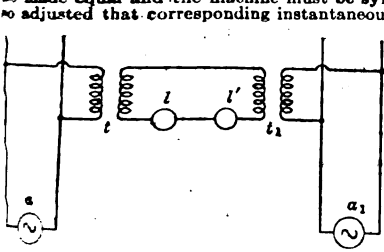


FIG. 109.—Connections for synchronizing with lamps.

288. The lamp method of synchronizing is the simplest. The principle of lamp synchronizers is shown in Fig. 109, where a, a_1 are the sources being connected in parallel and t, t_1 are transformers, the secondaries of which are connected in opposition through incandescent lamps, l, l_1. When the two sources are in synchronism, the secondary e.m.fs. neutralize each other and the lamps will be "dark." As the phase difference increases, the current through the lamps will increase, reaching a maximum at 180 deg. of phase difference. If the secondary of one transformer is reversed, the lamps will be brightest at synchronism and dark at 180 deg. of phase difference. The former connection is preferable because the point of total darkness" is more easily detected than the point of maximum "brightness." A voltmeter may be substituted for the lamps by connecting it so that synchronism is indicated when the reading is a maximum. The disadvantage of this method is that it does not indicate which frequency is the higher. Synchronism indicators (Par. 287) are instruments which not only overcome this objection, but indicate the point of synchronism more accurately.

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289. The principle of the Westinghouse synchroniser is shown in Fig. 110, where a rotating field is produced by the coils, *M* and *N*, connected to the buses through the reactance *P* and the resistance *Q*, respectively. An iron vane *A*, free to rotate, is mounted in this rotating field and magnetised by the coil *C*, which in turn is connected across the incoming machine. As the vane is attracted or repelled by the rotating field from *M* and *N*, it will take up a position where this field is zero at the same instant that the field from *C* is zero. Hence the position at any instant indicates the difference in phase. When the two frequencies are different, this position is constantly changing and the pointer will rotate "fast" or "slow," coming to rest at the zero-field position when the frequencies are equal. In a larger type, the split-phase winding is placed on the movable member, similar to the arrangement shown in Fig. 111.

290. The scheme of the Weston synchroscope is shown in Fig. 112. There is no iron in the instrument and the moving element is not allowed to rotate. The elements are practically the same as in an electrodynamometer wattmeter. The fixed coils, *F*, *F*, are connected in series with the resistance *R* and to the buses. The moving coil, *M*, is connected in series with a condenser *C* and the incoming machine. The two circuits are adjusted to exactly 90 deg. difference in phase. At synchronism there is no torque and *M* is held at the zero position by the control spring. If the frequencies are the same, but there is a phase difference, a torque will be exerted and *M* will move to a position of balance at the right or left ("fast" or "slow"). If the frequencies are different, the torque will continually vary and the pointer will oscillate over the dial. A synchronizing lamp illuminates the scale simultaneously and the direction of apparent rotation indicates the faster machine.

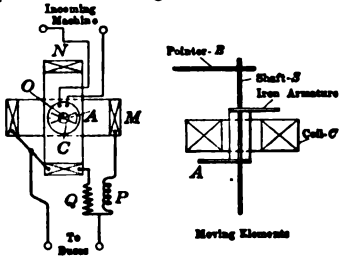


FIG. 110.—Circuits in Westinghouse synchroniser.

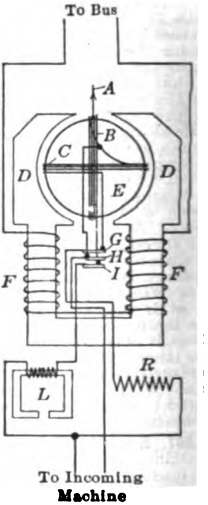


FIG. 111.—Circuits in G. E. synchroscope.

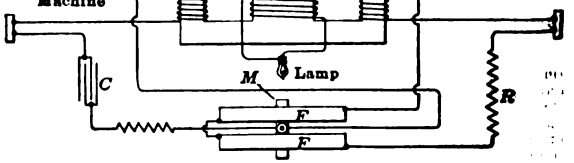


FIG. 112.—Circuits in Weston synchroscope.

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291. The General Electric synchroscope operates on the same principle as the Westinghouse instrument (Fig. 111). The split-phase winding, *C*, *B*, is mounted on the movable element, *E*, the two coils being connected to the incoming machine through slip-rings.

MAGNETIC MEASUREMENTS

292. General. The intensity of a magnetic field, $\mathfrak{H}$, may be considered the average fall of magnetic potential along the path and is expressed in gilberts per cm. In a long straight solenoid $\mathfrak{H} = 4\pi NI/10l$, where I = current in amperes and N/l = turns per unit length. **Magnetic induction or flux density,** $\mathfrak{B}$, is measured in lines of magnetic induction per square centimeter (gausses). When the substance in which the field exists is non-magnetic, $\mathfrak{B} = \mathfrak{H}$ and the ratio $\mathfrak{B}/\mathfrak{H}$, or permeability, is $\mu = 1$. When the substance is magnetic, $\mathfrak{B}$ becomes much greater than $\mathfrak{H}$, due to the decreased magnetic resistance; in general it varies with $\mathfrak{H}$.

293. The normal induction or $\mathfrak{B}$-$\mathfrak{H}$ curve of a magnetic material is the curve plotted between the strength of the magnetic field existing in the material, $\mathfrak{H}$, and the magnetic induction, $\mathfrak{B}$, produced by that field, when the material is in a neutral or normal condition. A **permeability curve** is plotted between the permeability μ and $\mathfrak{B}$, or between μ and $\mathfrak{H}$.

294. The hysteresis curve is a curve plotted between $\mathfrak{B}$ and $\mathfrak{H}$, for various values of $\mathfrak{H}$ from a maximum value in the positive direction to a maximum value in the negative direction, and back again, or through a complete cycle of values. The ends of a hysteresis loop will lie in the normal induction curve.

295. Magnetic measurements may be divided into two classes, (1) those in which the strength of a magnetic field is determined (such as the earth's field, the field due to a conductor carrying a current, the field in the air gap of a magnet, etc.) and (2) those made to determine the properties of magnetic material.

296. Field-strength measurements may be made by induction methods, with an oscillating bar magnet (Par. 299), or with a bismuth spiral (Par. 300). In the induction method a coil of known turns and area is so arranged that it can be made to cut the field in a known area in a direction perpendicular to the field. The e.m.f. generated in the coil, and hence the field producing it, is determined from the quantity of electricity discharged through a ballistic galvanometer connected to the coil terminals.

In measuring the field strength in air gaps, the coil is so arranged that one side can be moved quickly across the entire gap, or through a definite distance, by means of a spring or weight suddenly released. When there is sufficient space, a more accurate and convenient method is to rotate the coil through 180 deg. Very weak fields, such as the earth's field and that due to conductors, may be measured in this manner by using a sufficiently large coil.

297. Formula for field strength. The flux density in lines per square centimeter = $\mathfrak{B}$, and by definition equals in air

$$\mathfrak{H}(\text{field strength}) = \frac{10^8 dkR}{xan} \qquad \text{(gilberts per cm.)} \qquad (34)$$

where d = deflection, k = constant of galvanometer in coulombs per scale division, R = total resistance in galvanometer circuit, n = turns in coil, a = mean area of coil in square centimeters, x = linear distance moved in centimeters or, when the coil is turned through 180 deg., $x = 2$.

298. The Grassot fluxmeter is a portable instrument with which magnetic flux may be read directly on a scale. It is essentially a ballistic galvanometer with the moving element suspended by a torsionless suspension so that it remains deflected. The instrument is connected to an exploring coil which is placed in the air gap to be measured. The flux is measured by noting the deflection when the magnetising circuit is either opened or closed.

299. In the oscillating-magnet method, a small simple bar magnet is suspended by untwisted silk fibres. The magnet is set to vibrating through an angle of about 5 deg. and the period of oscillation determined. The average of at least three observations should be taken. The field strength is

$$\mathfrak{H} = \frac{4\pi^2 K}{MT^2} \qquad \text{(gilberts per cm.)} \qquad (35)$$

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where K = moment of inertia computed from the mass and dimensions, M = magnetic moment, and T = period of oscillation. M may be determined with a magnetometer, or by calibration in a known field (Helmholtz coil). This method is only suitable for weak fields, such as the earth's field. If mounted in a wooden box with a glass front, it will be protected from air currents and can be conveniently moved about when making magnetic surveys.

300. Bismuth-spiral method. The resistance of bismuth wire increases when placed in a magnetic field. This property is utilized by noting the increase in resistance of a flat spiral coil of bismuth wire when placed in the field to be measured, the leading-in wires being arranged non-inductively. The device is **calibrated** with known field strengths. It is particularly suitable for exploring small air gaps such as those in motors and generators.

301. Measurement of magnetic properties. The magnetic properties of iron and steel which are of most commercial importance are **normal induction** or **permeability, hysteresis loss** and **total losses** with alternating magnetizing forces of commercial frequencies.

302. Normal-induction data. The various methods are distinguished principally by the method employed to measure $\mathfrak{G}$, for in most methods $\mathfrak{H}$ is determined from the magnetizing coil. $\mathfrak{G}$ can be measured directly as in the **ballistic methods** or indirectly with **permeameters.**

303. Ballistic methods are usually employed in the more accurate measurements. The best-known methods are the **ring method,** the **divided bar** or Hopkinson, and the **double-bar double-yoke methods.** In all of these methods the flux is measured with a ballistic galvanometer connected to a test coil which is cut by the flux when the exciting current is reversed.

304. The ring method, devised by Rowland, is one of the earliest methods of measuring the magnetic properties of iron. The connections are shown diagrammatically in Fig. 113, where T is the test specimen. The latter is an annular ring, either solid or built up of punchings of sheet metal, with a diameter preferably 8 or 10 times the radial thickness. After covering with a thin layer of insulation, a test coil of very fine double-silk-covered wire is wound on a portion of the ring. The magnetizing coil is wound uniformly over the test coil and the entire ring. It is usually magnet wire, of sufficient size to carry the maximum current without raising the temperature of the iron appreciably. The formulæ are those in Par. **305,** except $2an$ instead of an.

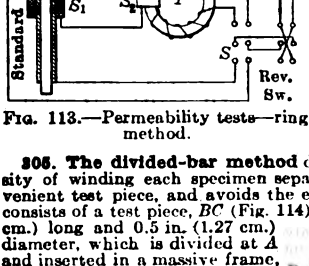


FIG. 113.—Permeability tests—ring method.

305. The divided-bar method devised by Hopkinson avoids the necessity of winding each specimen separately, permits the use of a more convenient test piece, and avoids the errors in ring specimens.* The device consists of a test piece, BC (Fig. 114), in the form of a bar about 15 in. (38.1 cm.) long and 0.5 in. (1.27 cm.) diameter, which is divided at A and inserted in a massive frame, F. The secondary coil, S, is so arranged that it will be thrown clear of the yoke by a spring when the part, AB, of the test bar is suddenly withdrawn. In calculating $\mathfrak{H}$, the length of the magnetic circuit is taken as that between the inside faces of the yoke, the reluctance of the yoke being considered negligible. This introduces an indeterminable



FIG. 114.—Permeability tests—divided-bar method.

* Lloyd, M. G. "Errors in Magnetic Testing with Ring Specimens;" Bureau of Standards, Bulletin, 1908, Vol. V, No. 3; p. 435.

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error and, therefore, the method can be suitable only for rough measurements. The leakage error due to flux through the coil, but not through the bar, can be determined by preliminary test with a non-magnetic bar. The formulæ for $\mathfrak{K}$ and $\mathfrak{G}$ are $\mathfrak{K} = 4\pi NI/10l$ and $\mathfrak{G} = 10^8 dkR/an$, where N = total turns of exciting coil, I = exciting current in amperes, l = length of magnetizing coil in cm. (NI/l = ampere-turns per cm.), d = deflection, R = total resistance of test coil circuit, k = galvanometer constant, a = area of specimen in square centimeter and n = turns in test coil.

306. The double-bar, double-yoke method is the one **recommended** by the **American Society for Testing Materials.** It was devised by

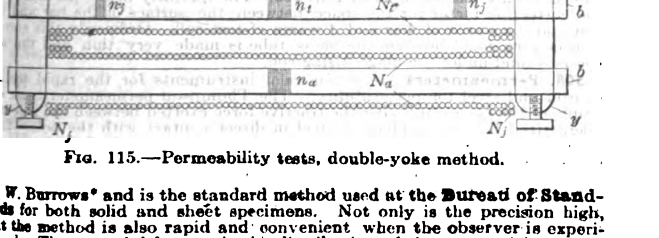


FIG. 115.—Permeability tests, double-yoke method.

C. W. Burrows* and is the standard method used at the **Bureau of Standards** for both solid and sheet specimens. Not only is the precision high, but the method is also rapid and convenient when the observer is experienced. The essential feature is the distribution of the magnetizing winding in sections, which permits the independent adjustment of the magnetizing force in various parts of the magnetic circuit. Thus the effect of non-uniform reluctance at joints, etc., can be overcome and the induction made uniform throughout the entire magnetic circuit. Exploring coils are placed at various positions so that the uniformity of the induction can be

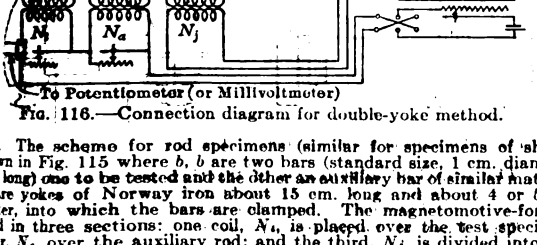


FIG. 116.—Connection diagram for double-yoke method.

tested. The scheme for rod specimens (similar for specimens of sheets) is shown in Fig. 115 where b, b are two bars (standard size, 1 cm. diameter, 35 cm. long) one to be tested and the other an auxiliary bar of similar material. y, y are yokes of Norway iron about 15 cm. long and about 4 or 5 cm. diameter, into which the bars are clamped. The magnetomotive-force is applied in three sections: one coil, N_t, is placed over the test specimen; another, N_a, over the auxiliary rod; and the third, N_j, is divided into four parts, one near each joint. The corresponding exploring coils are n_t, n_a and n_j. These coils all have the same number of turns, that is, $n_t = n_a =$ the two parts of n_j in series. They are so connected to a switch that n_a or n_t may be connected through the ballistic galvanometer in opposition to n_j, thus providing a zero method of determining uniformity of flux. The scheme of connections is shown in Fig. 116. The magnetizing coils are connected to special reversing switches so made that they can be operated simultaneously.

*Burrows, C. W. *Trans.* A. S. T. M., 1909, Vol. XI, p. 31.

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307. Procedure in double-bar double-yoke method. The method of procedure is as follows: After demagnetising (Par. 321), the current in N_i is adjusted to the value of $\mathfrak{H}$ required. The current in all magnetising coils is then simultaneously reversed several times to get the specimen in a cyclic condition, the current in N_s and N_i being adjusted during the process until the flux is uniform as indicated by zero deflection when n_s and n_i are successively opposed to n_t. The galvanometer is connected to n_t and the deflection noted when the current in the various magnetising coils is reversed simultaneously. Then

$$\mathfrak{H} = \frac{4\pi NI}{10\,l} \qquad \text{(gilberts per cm.)} \qquad (36)$$

$$\mathfrak{B} = \frac{10^8 dkR}{2an} - \left(\frac{A-a}{a}\right)\mathfrak{H} \qquad \text{(gausses)} \qquad (37)$$

The units are the same as in Par. 306. The quantity in the parenthesis is the correction factor for the space between the surface of the bar and the test coil. a = area of bar and A = area of test coil. Ordinarily this correction is very small because the brass tube is made very thin and the test coil is wound under the magnetising coil.

308. Permeameters are commercial instruments for the rapid testing of iron and steel for permeability. The Thompson permeameter is an example of the type employing the tractive force exerted between the pole of a magnetized bar and a piece of steel in direct contact with the pole. This force in dynes is $F = \mathfrak{B}^2 a/8\pi$, where $\mathfrak{B}$ = induction in bar in lines per square centimeter and a = area of bar in square centimeters. Koepsel and Picou permeameters are examples of induction-type instruments.

309. S. P. Thompson's permeameter is shown schematically in Fig. 117, where AB is the test specimen in the form of a rod which passes through a hole in the top of a heavy yoke, F. The surfaces of the end of the rod and the yoke at F are carefully machined. The force necessary to move the rod is measured with a spring balance at S. The induction is

$$\mathfrak{B} = 156.9\sqrt{\frac{P}{a}} + \mathfrak{H} \qquad \text{(gausses)} \qquad (38)$$

where $\mathfrak{B}$ = induction in lines per square centimeter (gausses) P = pull in grams and a = area of specimen in square centimeters.

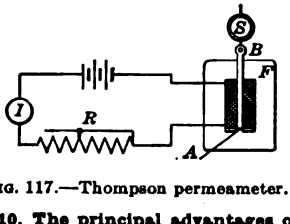


FIG. 117.—Thompson permeameter.

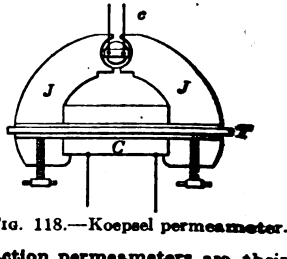


FIG. 118.—Koepsel permeameter.

310. The principal advantages of traction permeameters are their ruggedness and simplicity, which are important features in shop testing where rapidity is essential and only comparative data are required.

311. The Koepsel permeameter, as made by Siemens Halske, is shown schematically in Fig. 118, where JJ is a massive yoke divided at the centre so as to admit a moving coil c to which a pointer is attached, the arrangement being similar to standard D'Arsonval-type direct-current instruments. This pointer moves over a scale graduated directly in lines per square centimeter. The magnetic circuit is completed through the test piece T, firmly clamped between the ends of the yoke in the usual manner. The value of $\mathfrak{B}$ corresponding to various magnetising currents in C is indicated directly by the deflection with a known small current through c. Separate coils are placed on the yoke pieces, JJ, by means of which the reluctance of the various gaps is approximately compensated. But even with these coils, there is a flux leakage, so that correction or "shearing" curves have to be used.

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311a. The Esterline permeameter is a modification of the Koepsel apparatus which requires no corrections.*

312. The Picou permeameter is a double-yoke, single-bar instrument in which joint reluctances are compensated. The scheme is indicated in Fig. 119, where F_1, F_2 are the two yokes and T is the test specimen. The two auxiliary magnetising coils on F_1, F_2 are first connected with their magnetomotive forces in series. There is then supposed to be no flux in the test bar, its magnetising coil being out of circuit. The two coils on F_1, F_2 are then opposed and the current in the test-bar coil adjusted until the flux in F_1, F_2 is the same as before, as indicated by a ballistic galvanometer or otherwise. The conditions in the test bar are then supposed to be the same as in a long, uniformly magnetised bar. $\mathfrak{H}$ is calculated from the current and the constants of the test-bar coil as before, $\mathfrak{G}$ being measured with a test coil on the test bar.

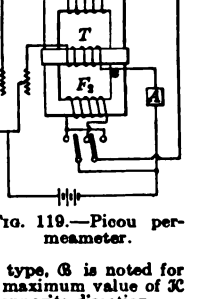


FIG. 119.—Picou permeameter.

312a. The Fahy permeameter is a recently developed induction-type permeameter of high accuracy† employing an H form of magnetic circuit. The distinctive feature is the measurement of $\mathfrak{H}$ with a separate test coil instead of the magnetising coil.

313. Hysteresis curves are obtained by any of the methods described above, for permeability tests, in which a coil is used to measure the flux. In direct-indicating permeameters such as the Koepsel type, $\mathfrak{G}$ is noted for various values of $\mathfrak{H}$, first descending from a positive maximum value of $\mathfrak{H}$ to the negative maximum, and then ascending in the opposite direction.

314. Ballistic step-by-step method of determining hysteresis. Where high precision is desired the ballistic "step-by-step" method is used. This method is carried out as follows: The current in the magnetising circuit is adjusted to a value corresponding to maximum $\mathfrak{G}$. It is then reversed a few times to get the specimen in a cyclic state. By means of suitable switching arrangements, some resistance is suddenly cut into the circuit, thus reducing $\mathfrak{H}$ to a new value, which is carefully noted. The corresponding change in $\mathfrak{G}$ is determined with a ballistic galvanometer in the usual manner. This process is continued, step by step, until zero current is reached, when the circuit is reversed and the resistance cut out, step by step, until the same maximum value of $\mathfrak{H}$ is reached in the opposite direction. The whole process is then repeated and the other side of the loop obtained. In this method, the errors will be cumulative, but can be eliminated by going back each time to the original maximum $\mathfrak{H}$; furthermore, it is then a simple matter to insure that the conditions remain constant, by occasionally checking the value of $\mathfrak{G}$ corresponding to maximum $\mathfrak{H}$.

Knowing the value of $\mathfrak{G}$ at the start, the values corresponding to the various steps in the step-by-step method are obtained by adding algebraically the various changes in $\mathfrak{G}$ to this initial value. The resulting values of $\mathfrak{G}$ and $\mathfrak{H}$ suitably plotted on cross-section paper form the **hysteresis loop.**

315. Hysteresis loss measurements. The area of the hysteresis loop, measured in the units of the ordinates of the curve (by planimeter or otherwise) and divided by 4π, gives the hysteresis loss in ergs per cubic centimeter per cycle, between flux densities $+\mathfrak{G}$ max. and $-\mathfrak{G}$ max. This method of measuring hysteresis loss is much too slow and expensive for commercial purposes, and several methods have been devised by means of which hysteresis losses can be measured directly, by electrical or mechanical means.

316. Robinson's method of measuring hysteresis loss. An example of an electrical method of measuring hysteresis loss is one used by L. T. Robinson.‡ It was designed primarily to reduce to a minimum the time and

* See Esterline, J. W., *Trans.* A. S. T. M., 1903, Vol. III, p. 288; 1908, Vol. VIII, p. 190.

† Burrows, C. W. and Sanford, R. L., "An Experimental Study of the Fahy Permeameter," Bulletin Bureau of Standards, Vol. 14, p. 267 (1917) (Scientific Paper No. 306).

‡ Robinson, L. T. "Commercial Testing of Sheet Iron for Hysteresis Loss;" *Trans.* A. I. E. E., 1911, Vol. XXX, 741.

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expense in preparing the sample, as well as the time spent in testing. The specimen is a bundle of strips 0.5 in. (1.27 cm.) × 10 in. (25.4 cm.), weighing 1 lb. (0.45 kg.). It is placed in a simple straight solenoid, with a sensitive wattmeter (reflecting electrodynamometer) in series with the magnetizing coil. A separate winding is provided for the wattmeter potential coil, thus simplifying the correction for the wattmeter loss. The induction is determined from the indication of a voltmeter, which is also connected to a separate winding at the centre of the specimen. The flux which it indicates is much higher than that at the ends, but experiment has shown that the ratio of the maximum to the average is 1.3 to 1. Due allowance is therefore made, when adjusting the magnetizing current to such a value that the voltmeter deflection will correspond to the required average flux-density. Measurements are made at 10 cycles, or less, in order to reduce the eddy-current loss to a point where it can be eliminated by means of empirical corrections without serious error. The precision obtained is about ±5 per cent.

317. In the Holden and the Ewing hysteresis meters, the loss is determined mechanically. In the Holden meter the test specimen, a ring of laminations about 1 cm. × 2 cm. (0.4×0.79 in.) cross-section, and 9 cm. (3.55 in.) diameter, is placed between the poles of a pair of revolving magnets. The torque exerted on the specimen is resisted by a spiral spring. The deflection of this spring which is necessary to bring the specimen back to the zero position is a measure of the loss in ergs per cycle.

The **Ewing apparatus** is operated on a similar principle, except that the specimen is rotated instead of the magnets. The specimen is a bundle of strip ½ in. (1.6 cm.) square and 3 in. (7.6 cm.) long.

318. Core-loss measurements. The total loss in iron or steel subjected to an alternating magnetic field is most accurately measured with a wattmeter. In making precision measurements, the Hopkinson ring-specimen can be used, but the Epstein apparatus is more convenient and has been adopted by the American Society for Testing Materials.* Fig. 120 shows the scheme diagrammatically.

The specimen is arranged in the form of a rectangle. The magnetizing winding is divided into four solenoids, each being wound on a form into which one side of the rectangular specimen is placed. The form is non-magnetic, non-conducting and has the following dimensions: inside cross-section, 4 cm. (1.57 in.) × 4 cm.; thickness of wall not over 0.3 cm. (0.12 in.); winding length, 42 cm. (16.5 in.). Each limb of the specimen consists of 2.5 kg. (5.5 lb.) of strips 3 cm. (1.18 in.) wide and 50 cm. (19.7 in.) long. Two of the bundles are made up of strips cut in the direction of rolling and two at right angles to the direction of rolling. The strips are held together with tape wound tightly around the bundle. The bundles form butt joints at the corners with tough paper 0.01 cm. (0.004 in.) thick between. They are held firmly in position by clamps placed at the corners.

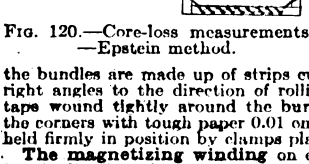


FIG. 120.—Core-loss measurements —Epstein method.

The magnetizing winding on each solenoid consists of 150 turns uniformly distributed over the 42 cm. (16.5 in.) winding-length, and has a resistance of between 0.075 and 0.125 ohm. A secondary winding is uniformly wound underneath the first; it also contains 150 turns in each solenoid, and energizes the potential circuit of the wattmeter and also the voltmeter with which the induction is measured. The resistance should not exceed 0.25 ohm per solenoid. With a sine-wave e.m.f. impressed on the magnetizing winding, the maximum induction is

$$\mathfrak{B} = \frac{E}{4} \frac{4}{fN} \frac{lD}{nM} 10^8 \qquad \text{(gausses)} \qquad (39)$$

where E = volts indicated by voltmeter, l = length of specimen, D = specific gravity (7.5 for alloy or high-resistance steels and 7.7 for standard or low-

* Standard Magnetic Tests of Iron and Steel; *Trans.* A. S. T. M., 1911; Vol. XI; p. 110.

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resistance steels), f = form factor of magnetizing electromotive force (1.11 for sine-wave), N = total secondary turns, n = cycles per second, and M = total mass in grams. The wattmeter gives the total loss in the iron, plus that in the secondary circuit. The latter is calculated from the resistance and the voltage, and deducted from the wattmeter reading.

319. For comparative commercial measurements of core losses, a single simple solenoid may be used.* The wattmeter indications are standardized with a standard sample. The accuracy obtained is quite sufficient for most factory purposes.

320. Separation of eddy-current and hysteresis losses in the core is usually accomplished by taking advantage of the fact that with a given value of B_{max}, the hysteresis loss varies directly with the frequency and the eddy-current loss with square of the frequency. The specimen is arranged as in a core-loss test and the loss noted at two frequencies, the induction being kept the same in the two cases. By means of two simultaneous equations, with two unknown quantities, both losses can be calculated.

321. Precautions in magnetic testing. Where the induction is measured by means of a stationary test coil surrounding the specimen, the space between the coil and the test specimen should be as small as possible. This can ordinarily be made so small that the leakage error is negligible.

Before induction measurements are made, the specimen should be carefully demagnetized. This is best done by first magnetizing to a value well above the maximum at which measurements will be made; the current is then gradually reduced to zero, being rapidly reversed meanwhile. Alternating current of 25-cycle frequency is convenient where much work is to be done.†

In loss measurements, the temperature of the specimen should be carefully noted, because this affects the eddy-current loss. The exciting winding should therefore be sufficiently large to avoid heating of the specimen. In precision work, the apparatus is placed in an oil bath.

In tests of sheet materials, the strips should not be too narrow, because of the hardening at the edges due to cutting. This effect is negligible with a width of 2 in. (5 cm.). Care should be taken that burrs are removed from the edges and that the only insulation between sheets is the natural scale of oxide. The test specimen should be composed of strips cut from the sheets in both directions.

The readings of a **ballistic galvanometer** should be kept at about the same magnitude by varying the resistance in series with it. The observational error is thus kept about constant.

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MECHANICAL POWER MEASUREMENTS

BY F. MALCOLM FARMER, M.E.

TORQUE MEASUREMENTS

323. Torque is best measured with dynamometers, of which there a two classes, absorption and transmission.* Absorption dynamometer absorb the total power delivered by the machine being tested, while tran mission dynamometers absorb only that part represented by friction in t dynamometer itself.

* Carpenter and Diedrichs. "Experimental Engineering" (Wile Sons, 1912). J. A. Moyer. "Power Plant Testing" (McGraw-Hill Boo Co., 1913).

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324. The Prony brake is the most common type of **absorption dynamometer.** It is simply a brake applied to the surface of a pulley on the shaft of the machine being tested, together with suitable means for varying the friction produced. The torque developed by the machine to overcome the friction is determined from the force required to prevent rotation of the brake.

325. The principal forms of Prony brakes are shown schematically in Figs. 121, 122, 123 and 124. In Fig. 121 the load is applied by tightening

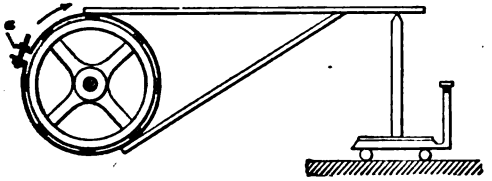
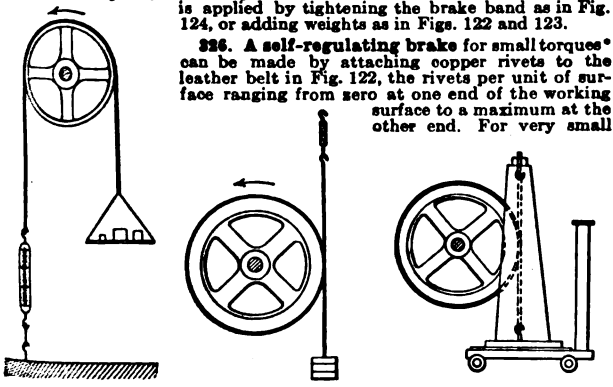


FIG. 121.—Prony brake.

the brake band at a, and the corresponding torque is measured by noting the force required at the end of a lever-arm of known length in order to prevent rotation. This force is usually measured with ordinary weighing scales or a spring balance. In Figs. 122, 123 and 124, the brake band is a belt or rope applied directly to the surface of the pulley, and the force is measured at the pulley surface by the various methods indicated. The load is applied by tightening the brake band as in Fig. 124, or adding weights as in Figs. 122 and 123.



326. A self-regulating brake for small torques* can be made by attaching copper rivets to the leather belt in Fig. 122, the rivets per unit of surface ranging from zero at one end of the working surface to a maximum at the other end. For very small

FIGS. 122, 123, and 124.—Prony brake.

torques a round belt in a grooved pulley and with small steel wire wound spirally around it, zero turns per inch at one end to maximum turns at the other, makes a simple and very satisfactory brake.

327. Formulas for calculation of torque from dynamometer measurements. The torque, T, in the various forms of Prony brakes (Par. 325) is determined as follows: In Fig. 121, $T = F_p L$, where F_p = force measured at end of brake-arm, L = length of brake-arm or distance from centre of shaft to point at which the force is measured. In Figs. 122 and 123, $T = (F_w - F_p)L$, where F_w = weight attached to end of brake-band, F_p = reading of spring balance, L = brake-arm = radius of pulley plus one-half the thick-

*H. M. Scheibe. "A Self-regulating Brake." *Electric Journal*, 1907, Vol. IV, p. 118.

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ness of belt or rope. In Fig. 124, $T = F_p L$, where F_p = force weighed on scales, L = brake-arm = radius of pulley plus one-half the thickness of belt or rope. If F and L are measured in pounds and feet respectively, T will be in lb. ft.

328. Dissipation of heat in friction brakes. The energy dissipated in the brake appears in the form of heat. In small brakes natural cooling is sufficient, but in large brakes special provisions have to be made to dissipate the heat. Water-cooling is the most common method, one scheme employing a flanged pulley. About 100 sq. in. of rubbing surface of brake should be allowed with air cooling, or about 50 sq. in. with water cooling per horse power.

329. For very large torques, other forms of absorption brakes are used. In the **Alden brake**, a rotating cast-iron disc rubs against thin copper discs which are held stationary. The friction is adjusted by varying the pressure of the cooling water in the chamber surrounding the copper discs. The tendency of the copper disc member to rotate is measured with a lever as in the Prony brake.

The **Westinghouse turbine brake** employs the principle of the water turbine and is capable of absorbing several thousand horse-power at very high speeds.

In the **magnetic brake**, a metallic disc on the shaft of the machine being tested is rotated between the poles of magnets mounted on a yoke which is free to move. The pull due to the eddy currents induced in the discs is measured in the usual manner by counteracting the tendency of the yoke to revolve.

330. The principal forms of transmission dynamometers are the lever, the torsion and the cradle types. An example of the **lever type** is

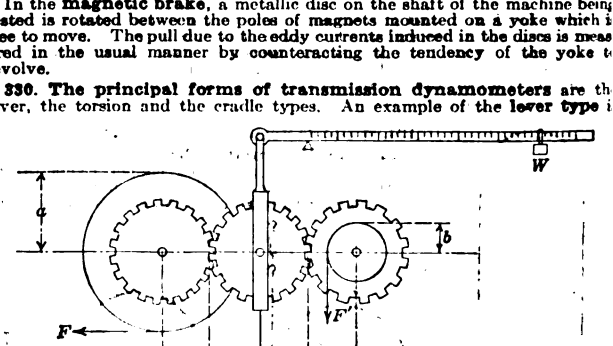


FIG. 125.—Transmission dynamometer.

shown in Fig. 125, where F is the force applied to the dynamometer, and F' is the force being delivered. When the downward force, X, is balanced by the weight W, the following formula holds,

$$F = \frac{1/2(1+\mu)Xr}{a} \qquad (40$$

where μ = coefficient of friction determined experimentally.

331. In torsion dynamometers, the deflection of a shaft or spiral spring which mechanically connects the driving and driven machines, is used to measure the torque. The spring or shaft can be calibrated statically by noting the angular twist corresponding to a known weight at the end of a known lever-arm perpendicular to the axis. When in use the angle can be measured by various electrical and optical methods. In one method the angular displacement between two points on the shaft is determined by means of two discs of insulating material, in the periphery of each of which is set a very thin piece of metal. The two pieces of metal are connected electrically through the shaft. A light, thin metal brush rests on the periphery of each disc, and the two brushes are connected together through a battery and an indicator such as a bell, or a telephone. At no load, one brush is moved until the electrical circuit is completed once every revolution. The

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angle through which either brush has to be moved as the load is increased, in order to keep the circuit closed, is then measured.

331. The cradle dynamometer is a convenient and accurate device which is extensively used for routine measurements of the order of 100 h.p. or less. An electric generator is mounted on a "cradle" supported on trunnions and mechanically connected to the machine being tested. The pull exerted between the armature and field tends to rotate the field. This torque is counterbalanced and measured with weights moved along an arm in the usual manner.

SPEED MEASUREMENTS

333. Revolutions are measured with speed counters and tachometers. **Speed or revolution counters** are attached directly to the shaft to be measured and record the total revolutions from the instant that the mechanism is connected. They usually consist of an arrangement of worm and gears, the total revolutions being shown by a graduated dial moving under a pointer, or by a cyclometer dial on which the total revolutions are indicated numerically at each revolution. In order to obtain the speed, the intervening time must be observed simultaneously.

334. Tachometers or speed indicators indicate the speed directly and thus include the time element. The principal types are centrifugal, liquid, reed and electrical. In the centrifugal type, a revolving weight on the end of a lever moves under the action of centrifugal force in proportion to the speed, as in a fly-ball governor. This movement is indicated by a pointer which moves over a graduated scale. In the portable or hand-type, the tachometer shaft is held in contact with the end of the shaft being measured, and in the stationary type, the instrument is either geared or belted. In the liquid tachometer of the Veeder type, a small centrifugal pump is driven by a belt consisting of a light cord or string. This pump discharges a colored liquid into a vertical tube, the height of the column being a measure of the speed.

Reed tachometers are similar to reed-type frequency indicators (Par. 279), the reeds being set in resonant vibration corresponding to the speed of the machine, by various means. The instrument may be set on the bedframe of the machine where any slight vibration due to the unbalancing of the reciprocating or revolving member will set the corresponding reed in vibration. Some forms are belted to the revolving shaft and the vibrations imparted by a mechanical device. **Electrical tachometers** may be either reed instruments operated electrically from small alternators geared or belted to the machine being measured, or ordinary voltmeters connected to small permanent-magnet, direct-current generators driven by the machine being tested.

335. Chronographs are speed-recording instruments in which a graphical record of speed is made. In the usual forms, the record-paper is placed on the surface of a drum which is driven at a certain definite and exact speed by clock-work or weights, combined with a speed-control device so that 1 in. on the paper represents a definite time. The pens which make the record are attached to the armatures of electromagnets. With the pens in contact with the paper and making a straight line, an impulse of current causes the pen to make a slight lateral motion and therefore a sharp indication in the record. This impulse can be sent automatically by a suitable contact-mechanism on the shaft of the machine or by a key operated by hand. The time per revolution is then determined directly from the distance between marks.

THERMOMETRY, PYROMETRY AND HEAT CONDUCTIVITY

BY G. K. BURGESS, SC.D.
AND
PAUL D. FOOTE, Ph.D.

THERMOMETRY

336. Temperature scale. The standard temperature scale is fixed in the interval −40 deg. to 450 deg. cent. by means of the platinum resistance thermometer calibrated in ice, steam, and sulphur vapor (444.6 deg. cent.).

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In the interval 450 deg. to 1100 deg. cent. it is defined by the fixed point melting points of antimony (or aluminum) and of gold (or copper), and interpolation between these points is based on the temperature scale defined by the rare-metal thermocouple (Pt, 90Pt10Rh) calibrated at these two temperatures and a third temperature, melting point of zinc as determined by the resistance thermometer. The temperature scale above 1100 deg. cent. is based upon the extrapolation of Wien's law using as the fiducial point the melting point of gold = 1063 deg. cent. and $c_2 = 14{,}350$ micron deg.

337. High temperature thermometers. Mercury in glass thermometers are useful from −35 deg. to 550 deg. cent. In order to prevent vaporisation of the mercury at high temperatures the top of the capillary is filled with nitrogen under pressure. The thermometer must be well annealed at as high a temperature as the glass will safely stand. Errors of 1 deg. or more may result from imperfect annealing. **Industrial mercury-in-glass thermometers** have the bulb encased in a metal tube and the stem is well protected by a metal frame. This construction introduces two questionable factors, lag and conduction of heat along the frame. It is consequently necessary that the instruments be used for the purpose designed. Industrial thermometers calibrated to read gas temperatures will not necessarily give true temperatures when immersed in liquids. **Indicating thermometers** of the dial and pointer type and **recording thermometers** employing a mechanism for recording temperatures on a chart are of three classes, electrical (thermocouple or resistance) thermometers, pressure thermometers, and bimetallic thermometers. Pressure thermometers consist of a bulb containing a liquid or gas or both, connected by capillary tubing to a pressure gage graduated to read temperature. Bimetallic thermometers utilize the turning moment produced when a strip of two metals of different expansion coefficient and brazed together is heated. These instruments are not as accurate as mercury-in-glass thermometers but are very useful and are extensively employed.

338. Low-temperature thermometers. For the measurement of temperatures below the range of the mercury thermometer (− 35 deg. cent.) there are available alcohol (−70 deg. cent.), toluene (−90 deg. cent.), and petroleum-ether or pentane (−200 deg. cent.) liquid-in-glass thermometers, copper-constantan and other thermocouples, and electric resistance thermometers. With these types of liquid-in-glass thermometers the same precautions apply as with mercury, and in addition special care must be taken to prevent the liquid from sticking to the sides of the glass. On account of viscosity of the liquid at low temperatures the thermometer must be slowly cooled to the temperature of the bath, cooling first the bulb and then the stem.

339. Correction for emergent stem of mercury-in-glass thermometers. Thermometers are usually graduated for total immersion in a bath, while frequently in later use part of the stem protrudes from the bath and may be at a considerably different temperature. Under such conditions the following stem correction should be added to the observed reading. Stem correction $= Kn(T^\circ - t^\circ)$, in which $K = 0.00016$ for centigrade thermometers and 0.00009 for fahrenheit thermometers; n = number of degrees emergent from the bath; T = temperature of bath; t = temperature of emergent stem. The value of t may be roughly measured by an auxiliary thermometer the bulb of which is placed about three-fourth the distance down the exposed mercury column. Stem corrections may amount to 40 deg. or more at high temperatures and hence become very important where accuracy is desired.

340. Calorimetric mercury thermometers are of two types, the ordinary mercury thermometer with a total stem length of 10 to 15 deg. cent., graduated in 0.05-deg. to 0.02-deg. intervals, and the **Beckmann thermometer** arranged so that part of the mercury may be removed from the bulb in order to utilise the short scale (5 or 6 deg. cent. graduated in 0.01-deg. intervals) for differential work at various temperatures. In addition to the stem corrections the Beckmann type requires a setting correction depending upon the amount of mercury remaining in the bulb. Calorimetric thermometers may be in error by 1 per cent. of the indicated temperature scale differences, and consequently should be calibrated. The highest accuracy attainable is from 0.5 to 0.1 per cent. For greater precision thermocouples or resistance thermometers are available.

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PYROMETRY

341. Thermoelectric pyrometry. In pyrometers of this type temperatures are measured by the magnitude of the electromotive forces set up between wires of different materials when one junction is exposed to the temperature to be measured and the other junction (or junctions) is kept at some known temperature.

342. Material of couple. Couples extensively employed are: copper-constantan to 360 deg. cent.; iron-constantan to 900 deg. cent.; alumel-chromel or nichrome-alumel to 1100 deg. cent.; (Pt−90Pt10Rh) from 300 to 1500 deg. cent. The following table shows the calibration data of these couples, based on a cold junction temperature of zero deg. cent. Different rare-metal couples of the same type should be reproducible to ±2 deg. cent. and base metal couples to ±10 deg. cent.

343. Calibration Data of Representative Couples

Cold-junction temperature, 0 deg. cent. E.m.f. in millivolts

Engelhard "Le Chatelier"		Johnson-Matthey "Le Chatelier"		Copper-constantan		Iron-constantan			Chromel-alumel	
							Deg. cent.			
E.m.f.	Deg. cent.	E.m.f.	Deg. cent.	E.m.f.	Deg. cent.	E.m.f.	*B*	*L*	E.m.f.	Deg. cent.
0	0	0	0	0	0	0	0	0	0	0
1	147	1	146	1	25	5	105	95	5	122
2	265	2	260	2	49	10	204	186	10	243
3	374	3	364	3	72	15	299	277	15	363
4	478	4	461	4	94	20	392	367	20	482
5	578	5	553	5	115	25	483	457	25	601
6	675	6	641	6	136	30	574	546	30	721
7	770	7	725	7	156	35	662	632	35	844
8	861	8	806	8	175	40	749	713	40	970
9	950	9	884	9	194	45	836	792	45	1100
10	1037	10	959	10	213	50	924	871		
11	1122	11	1032	11	232	55	1011	950		
12	1206	12	1103	12	250	60	....	1030		
13	1290	13	1173	13	268					
14	1373	14	1242	14	285					
15	1455	15	1311	15	302					
		16	1379	16	319					
		17	1447	17	336					
				18	353					

B represents mean calibration by U. S. Bureau of Standards of iron-constantan couples from all sources. *L* represents mean calibration of Leeds & Northrup's iron-constantan couple.

344. Measuring instruments. The instruments employed to measure thermoelectric e.m.f.'s operate on the galvanometric principle, potentiometric principle, or a combination of these. Since the e.m.f.'s are small the galvanometers, which are essentially ammeters graduated to read e.m.f., must be very sensitive to voltage. This could be accomplished by using an instrument of low resistance but on account of the variable line resistance of a thermoelectric circuit it is necessary to make the resistance of the galvanometer as high as possible, consistent with substantial construction. If the indicator is graduated to read e.m.f. at its terminals the relation between scale reading e_s and true e.m.f. of the couple e becomes $e_s = R_g e/(R_g + R_c + R_L)$, where R_g, R_c and R_L denote the resistances of the galvanometer, couple and lead wires respectively. If R_g is large compared to $R_c + R_L$ the above equation reduces approximately to $e_s = e$ and the indicator reads cor-

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rectly. When R_g is low it is still possible to graduate the scale to read tr e.m.f. for a definite line resistance, but if this changes on account of d terioration of the couple, etc., serious error may result. Thus a 300-oh indicator designed for use with a 2-ohm line resistance will be in error b only 7 deg. at 1000 deg. cent. if the line resistance changes to 4 ohms, whi a 10-ohm indicator under similar conditions would read 140 deg. cent. to low. This emphasizes the importance of the use of galvanometers of hig resistance.

345. The Brown Heat Meter (Harrison-Foote Method), is a compe sated millivoltmeter which eliminates errors arising from variable line r

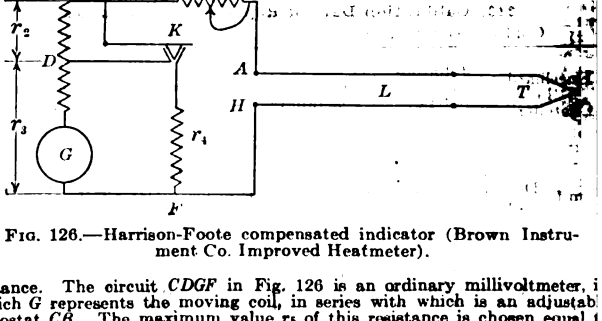


FIG. 126.—Harrison-Foote compensated indicator (Brown Instrument Co. Improved Heatmeter).

sistance. The circuit *CDGF* in Fig. 126 is an ordinary millivoltmeter, i which *G* represents the moving coil, in series with which is an adjustab rheostat *CB*. The maximum value r_5 of this resistance is chosen equal t the maximum line resistance likely to occur in practice, a convenient valu being 15 ohms. With the rheostat set for $r_1 = r_5$, the instrument is graduate to read potential drop across *AH*. Hence in use r_1 should be adjusted unt $r_1 + L + T = r_5$. This adjustment is made by moving r_1 until no change i deflection is produced by depressing the key *K*. By properly proportionin the various resistances, this setting may be easily made to correct for change in line resistance which would occasion an error of only 0.01 scale divisio The method accordingly is exceedingly sensitive, yet so simple that it in n manner complicates the use of the indicator. The device is adaptable t multiple installations either with indicators or recorders.

346. Potentiometers. The most accurate method for measurin thermoelectric e.m.f.'s is by means of the potentiometer, the principle o operation of which is described in Par. **49** to **52**. Special low-range instru ments adapted to pyrometry are made by Leeds and Northrup. Th company also makes a **portable potentiometer** for either rare-metal o base-metal couples, or for both with a double scale. The potentiomete affords the advantage that its indications are independent of line resistanc On the other hand a balance must be effected for each reading, so that th instrument is not so convenient for general practice as a high-resistanc galvanometer. It is possible to employ the potentiometric principle with a indicating instrument. Thus the galvanometer may be used as an ammet in adjusting the battery current through the potentiometer to a fixed valu and then it may be connected by a suitable switch into the couple circu and used as a detector for zero current or balancing. It is also possible t arrange the circuit so that after the balance the galvanometer deflec showing the true e.m.f., as is done in the **Northrup Pyrovolter.** Th deflection potentiometer principle (Par. **54**) has been employed advanta eously in pyrometry but at present the method is not used very extensivel

347. Cold-junction corrections. If a couple is calibrated with a co junction temperature of t_0 deg. cent. and used with a cold junction tem perature of t'_0, it is necessary to add to the observed e.m.f. the value o the e.m.f. developed when the hot junction is at t'_0 and the cold junction

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is to obtain correct temperature from the calibration data. If the indicator is graduated in temperature add to the observed reading $(t'_0 - t_0)K$, where K is a factor depending upon the couple and temperature. Values of K for typical couples are as follows (Par. 348):

348. Cold-junction correction factors

Engelhard "LeChatelier"		Johnson-Matthey "LeChatelier"		Copper-constantan		Iron-constantan	
Deg. cent.	K*	Deg. cent.	K*	Deg. cent.	K*	Deg. cent.	K*
265–450	0.65	250–400	0.60	0–50	1.00	0–100	1.00
450–650	0.60	400–550	0.55	50–80	0.95	100–600	0.95
650–1000	0.55	550–900	0.50	80–110	0.90	600–1000	0.85
1000–1450	0.50	900–1450	0.45	110–150	0.85	Chromel-alumel	
				150–200	0.80	0–800	1.00
				200–270	0.75	800–1100	1.05
				270–350	0.70		

*Based on calibration with $t_0 = 0$ deg. cent.

349. Compensators. Various methods are employed for avoiding the necessity of making these corrections. Simple indicators may be set on open circuit to read the cold junction temperature. Potentiometric instruments may be equipped with either manually or automatically operated compensators. Even with such devices, however, it is desirable to control the cold junction temperature as much as feasible. This may be done by water jacketing the terminal head of the couple, but preferably by extending the cold junction to a region of fairly constant temperature. With base-metal couples, extension leads of the same material are used and with rare-metal couples leads consisting of one wire of copper and the other an alloy of copper and nickel. The compensating leads are carried directly to the indicator which is located in a room of reasonably constant temperature, or may terminate in a buried cold junction from which copper lead wires run to the instrument. The buried cold junction is made by driving a pipe underground to a depth of 10 feet. After inserting the cold junctions the top should be well protected from moisture.

350. Thermocouple installations. Competent electricians should make couple installations. Lead wires should be weather proof and protected by grounded conduit. All joints in wires should be soldered and taped. If the indicators have a low resistance special attention must be given to switches. Frequently switches rated at 100 amperes must be used although the thermoelectric current is only a few milliamperes. Copper wire as large as No. 10 or 12 may be necessary for long lines in order to keep the resistance low. The choice of a proper protecting tube is nearly as important as the selection of the couple. Quartz, porcelain, carborundum, nichrome, chromel, graphite, fireclay, alundum, nickel, iron, colorized iron, etc., all have their special applications for certain processes. In multiple installations the common return should not be employed on account of the danger from short circuits and leakage. Galvanometric instruments of low resistance designed for separate connection should not be operated in parallel. Compensating wire should not be used extravagantly as it is costly and increases the line resistance. The use of a **junction box** minimizes the amount of compensating leads required. This consists of a heavy cast-iron box mounted near a multiple couple installation, inside of which the copper-compensating lead junctions are located. The e.m.f. developed at these junctions is corrected for by a common junction in the opposite direction inserted between the selective switch and the indicator or recorder. The common cold junction may be buried under ground. Fig. 127 shows

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the wiring diagram. On a coke oven installation of nine couples it is thus possible to save 600 feet of compensating cable.

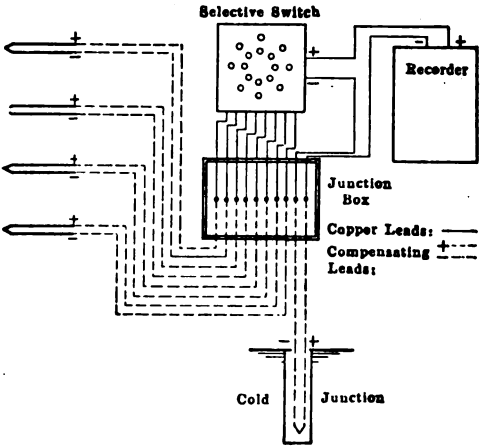


FIG. 127.—Illustrating use of junction box with controlled cold-junction temperature.

351. Electrical resistance pyrometry. This method of high-temperature measurement ordinarily makes use of the variation in the electrical resistance of platinum and is capable of great sensitivity. In one of its simplest forms the pyrometer consists of a coil of platinum wire wound on mica, and encased in a protecting tube of porcelain. On account of the distillation of platinum, high-resistance coils of small wire are not used much above 900 deg. cent. However, coils constructed of 0.6-mm. wire may serve satisfactorily to 1,200 deg. cent. for investigational work.

352. Three-lead type—Wheatstone bridge method. For the purpose of eliminating the resistance of the leads to the coil, a third wire is

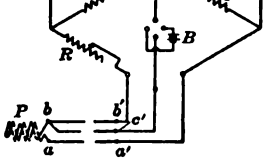


FIG. 128.—Three-lead resistance thermometer.

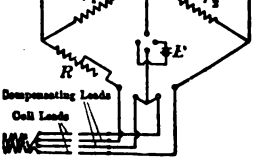


FIG. 129.—Four-lead resistance thermometer.

frequently introduced as in Fig. 128. The coil P forms one arm of a dial-type bridge, of which the others are r_1, r_2 and R, whence from the principle of the bridge, if the galvanometer G remains undeflected,

$$P = \frac{r_2(R + bb')}{r_1} - aa' \qquad (41)$$

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n is usually made equal to r_1 and bb' is constructed as nearly as possible identical with aa', so under these circumstances $P = R$ regardless of the temperature or resistance of the leads. This type of thermometer may also be used with a differential galvanometer.

353. Four-lead type—Wheatstone bridge method. The compensating leads are inserted in one arm of the bridge R and the thermometer leads in the other, as shown in Fig. 129. This type may be used with a slide-wire bridge.

354. Four-lead potential-terminal type (Fig. 130). The resistance of the coil is measured by sending the same current from a storage battery through the thermometer and a known resistance in series, and measuring the potential drop by means of a potentiometer, first across the known resistance and then across the thermometer coil. Two of the thermometer terminals are current leads and two are potential leads. The current ordinarily used is of the magnitude 0.003 to 0.05 amp., and should be the same as that used during the calibration of the instrument, to eliminate the errors due to the heating effect of this current.

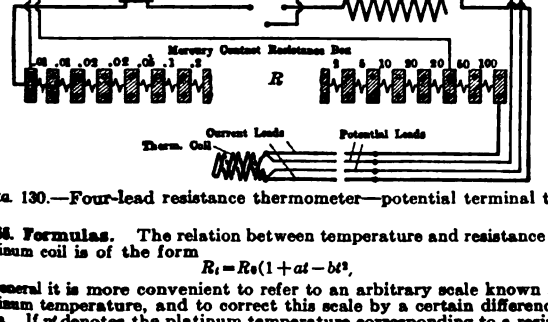


FIG. 130.—Four-lead resistance thermometer—potential terminal type.

355. Formulas. The relation between temperature and resistance of the platinum coil is of the form

$$R_t = R_0(1 + at - bt^2), \tag{42}$$

In general it is more convenient to refer to an arbitrary scale known as the platinum temperature, and to correct this scale by a certain difference formula. If pt denotes the platinum temperature corresponding to a resistance R, we have the relation

$$pt = \frac{100(R - R_0)}{R_{100} - R_0} \tag{43}$$

where R_{100} and R_0 are the resistances at 100 deg. cent. and 0 deg. cent. respectively. The relation between the centigrade temperature t and the platinum temperature pt is as follows:

$$t - pt = \frac{\delta\left(\frac{t}{100} - 1\right)}{100} t \tag{44}$$

356. Calibration. For the calibration of a thermometer, the coil of which is of the highest purity platinum, resistance measurements are made at three temperatures, as follows: the ice point, the steam point and the boiling point of sulphur. Substituting the values thus obtained in formula for pt (Par. 355) the value of pt corresponding to the sulphur point is known. Referring to the formula for t (Par. 355), the value of δ should be found a constant of the magnitude 1.49 ± 0.01, whence from the two formulas a table of R and t may be computed. Such a calibration will indicate temperatures in the range -50 to 1,200 deg. cent. as closely as they are known in terms of the gas scale. If δ is found considerably greater than 1.49 on account of impurity of the platinum, there is advantage in using a fourth calibration point, such as the silver freezing-point as a check.

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357. Adaptability. The **resistance thermometer** is especially adap to the measurement of small temperature changes such as occur in cal imetry, to the determination of freezing-points, etc., and to special physi and thermochemical investigations where an accuracy of one or two pa in 10,000 may be attained (see Bur. of Standards, Sci. P. No. 68 and 124). In the technical industries this type of thermometer with one of many forms of indicators available is employed for special processes but general a thermocouple installation is more satisfactory.

358. Radiation. The temperature of bodies may be estimated from radiant energy which they send out in the form of visible light or of the lon infra-red rays which may be detected by their thermal effects. Since intensity of radiation increases very rapidly with a rise in temperature, would appear that a system of pyrometry based on the intensity of the li or total radiation from a hot body would be an ideal and simple one. Ho ever, different substances at the same temperature show vastly differe intensities at a given wave length, or in other words, the **absorbing or em sive powers** may vary with the substance, with the wave length and a with the temperature.

359. Black-body radiation. A substance which absorbs all the rad tion of any wave length falling upon it is known as a **black body.** Such body will emit the maximum intensity of radiation for any given temperatu and wave length. No such material exists, but a very close approximati is obtained by heating the walls of a hollow opaque enclosure as uniformly possible and observing the radiation coming from the inside through a ve small opening in the wall.

360. Stefan-Boltzmann law. The relation between the total ener radiated by a black body and its temperature is expressed by the equati $J = \sigma(T^4 - T_0^4)$, where J is the energy of all wave lengths emitted per seco per square centimeter of surface, T and T_0 the absolute temperatures of t radiator and surroundings respectively, and σ a constant of the value 5.7 10^{-12} watts cm.$^{-2}$ deg.$^{-4}$. In general T_0^4 is negligible in comparison with so that the above relation becomes $J = \sigma T^4$. Although the total energy em ted by any substance is not that emitted by a black body at the same te perature, it may be considered as some fractional part of that from the id radiator, this fraction E being known as the **total emissivity.** If S deno the apparent absolute temperature, i.e., the temperature on the blac body scale corresponding to an amount of energy equivalent to that emitt by the non-black substance at a true temperature T deg. absolute, the lation between its total emissivity E and the quantities S and T is:

$$\text{Log } E = 4(\log S - \log T) \qquad (4$$

361. Radiation pyrometry. Féry mirror telescope pyrometer (Fig. 131.) Radiation of all wave lengths is brought to a focus by mea of a concave gold mirror M upon the hot junction of a minute thermocouple located at T. The cold junctions of the couple are suitably screened from the direct radiation of the hot body. The concentration of heat at the hot junction develops an e.m.f. which may be measured by a potentiometer or galvanometer. In practice the galvanometer is usually calibrated to read temperature directly. The relation between the e.m.f. and the temperature for this and other types of radiation pyrometer may be expressed by the equation $e = aT^b$, or in log form, $\log e = k + b \log T$, where T is the absolute temperature and a or k and b are empiric constants. In general b approximates the value 4, but may have a ran varying from 3.5 to 4.5 depending upon the construction of the individu instrument. The pyrometer should be sharply focused upon the radiati source and for this purpose an ingenious device is mounted in the instrume by means of which straight lines appear broken until the mirror is adjust by the thumb screw S to the proper position. **Foster** has transformed t

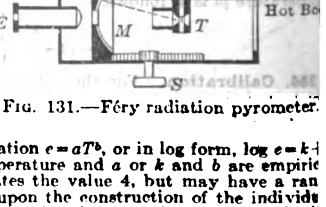


FIG. 131.—Féry radiation pyrometer.

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Fery telescope into a fixed-focus pyrometer by placing the thermocouple and a small front diaphragm at the conjugate foci of the gold mirror.

362. Thwing pyrometer. In the Thwing pyrometer the reflecting mirror is replaced by an aluminum cone which by multiple reflections concentrates the radiation at its apex on one or more small thermocouples in series with a portable galvanometer. The instrument requires no focusing, the front diaphragm acting as a source. The object sighted upon must be large enough to cover the projection of the cone through this diaphragm.

363. Precautions in the use of radiation pyrometers. The mirrors or reflecting devices must be kept bright and free from dust. In the case of the Féry pyrometer, errors amounting to 100 deg. cent. have been observed, on account of ordinary accumulation of dirt upon the large gold mirror.

Many radiation instruments require several minutes of exposure to the radiating source to indicate a maximum reading on account of the slow heating of the hot junction, while others require less than 20 sec. The maximum indication should be accepted. Care must be taken that the source is large enough to completely "fill" the aperture of the pyrometer. It is usually impossible to focus upon the back of a furnace through a very small peep-hole and obtain reliable results; in such cases the hole must be enlarged so that it does not cut into the cone of rays entering the instrument, or the pyrometer may be focused upon the hole itself. In the latter case the hole must be large enough to cover the thermocouple in the Féry pyrometer or the front diaphragms of the Thwing and Foster pyrometers. Variations in room temperature in general affect the hot and cold junctions nearly alike, so that very little error is introduced in the reading of a radiation instrument from this cause. It is desirable to employ the same ratio of diameter of source sighted on to sighting distance both in calibration and use of all radiation pyrometers.

364. Emissivity corrections for radiation pyrometers. In the case of sighting upon peep-holes in furnaces, kilns, etc., the total-radiation pyrometers indicate approximately true temperatures. When sighting upon objects in the open, certain corrections must be applied. These corrections are but roughly known. The following table (Par. 365) shows the true temperatures corresponding to the pyrometer indications when sighting upon molten iron ($E=0.28$), molten copper (0.15), copper oxide (0.60), iron oxide, and nickel oxide. The data are obtained from the work of Thwing, Burgess and several experiments of the authors.

365. Total Emissivity Corrections

Observed temperature, deg. cent.	True temperature, deg. cent.				
	Molten iron	Molten copper	Copper oxide	Iron oxide	Nickel oxide
600	.....	1,130	720	630	710
700	.....	1,290	830	735	800
800	1,200	.....	945	835	895
900	1,340	.....	1,060	940	985
1,000	1,475	.....	1,170	1,040	1,075
1,100	1,610	.....	.....	1,145	1,165
1,200	1,750	.....	.....	1,250	1,255

366. Wien's law. Wien's laws relate to the distribution of the energy of the black body in the spectrum. The law chiefly concerned in optical pyrometry expresses the relative intensity of the energy emitted at any given wave length λ and temperature in the following manner:

$$J_\lambda = c_1 \lambda^{-5} e^{-\left(\frac{c_2}{\lambda T}\right)} \qquad (46)$$

where J_λ is the energy corresponding to the wave length λ and the absolute temperature T of the radiator, e the base of the natural (Napierian) system of logarithms, and c_1 and c_2 empirical constants. c_2 may be taken as 14,350 when λ is measured in microns, *i.e.*, μ (Sec. 1). If S_λ is the apparent

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absolute temperature corresponding to the wave length λ of a non-bla body at a true absolute temperature T, it follows that

$$\frac{1}{T}-\frac{1}{S_\lambda}=\left(\frac{\lambda}{c_2 \log e}\right)\log E_\lambda=\frac{\lambda \log E_\lambda}{6232} \qquad (4$$

where E_λ = emissivity = unity minus reflecting power of the radiator at t particular wave length λ and temperature T.

367. Optical pyrometry. Optical pyrometers are based upon t photometric principle of matching the intensity of visible monochroma radiation emitted by a substance, with that of the same wave length color from a standard reproducible source such as the amylacetate lamp, a constant source such as an electric lamp. The instruments are calibrat by comparison with the intensity of radiation from a black body, the prima standard to which all measurements are referred.

368. Féry absorption pyrometer. (Fig. 132.) The apparatus co sists essentially of a telescope carrying a small oil or gasoline lamp L. T image of the flame of this lamp is projected on a silver strip at M adjust to the focal point of the ocular and objective system. By means of t black-glass absorbing wedges w, w, the intensity from the source may varied until a match of the photometric field (see small Fig.) is obtained. A red-glass screen is used in the ocular so that fairly monochromatic light of this color (0.65 or 0.63μ) is compared. The relation between the thickness of the wedges x, read on a scale, and the absolute temperature T is $x+P=Q/T$, where P and Q are constants determinable by two calibration points. The instrument must be focused upon the radiatin source but no corrections for distance need be applied. The **LeChatelie pyrometer,** the first optical pyrometer developed, is similar in princip but is not of constant aperture and important corrections must be mad with change of focus. The **Shore pyroscope** has a direct-reading tem perature scale controlled by a diaphragm before the standard oil lam In all of these instruments the purity of the gasoline, oil, or even t amylacetate used in the comparison lamps is of little importance. Co siderable impurity may be introduced without affecting the calibratio perceptibly. The **F. and F.** pyrometer employs a semi-circular wedge as an electric lamp with the filament in the line of sight.

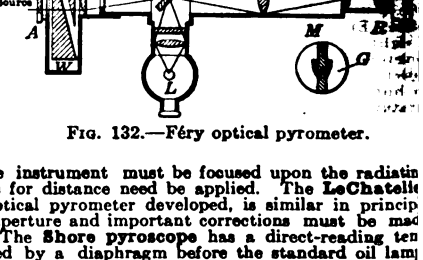


FIG. 132.—Féry optical pyrometer.

369. Wanner pyrometer. (Fig. 133.) The comparison light is a si volt incandescent lamp illuminating a glass matt surface; monochromati red light is produced by means of a direct-vision spectroscope P and a slit cutting out all but a narrow band in the red ($\lambda = 0.65\mu$) and the phot metric comparison is made by adjusting to equal brightness both halves the photometric field by means of a polarizing arrangement. The slit is illuminated by the incandescent lamp while light from the furnace enters After passing through a Wollaston prism and a biprism, the light from two slits polarized in planes at 90 deg. to each other reaches the Nicol pri N. Rotation of this analyzer serves to extinguish one field and bright the other simultaneously, until a match is effected. A reference angle chosen, usually about 30 deg., corresponding to the apparent temperat of a section of an amylacetate flame. The instrument is set at this norm point and sighted upon the ground-glass screen of the flame gage. T brightness of the electric lamp is then varied by altering the current throu it until the halves of the photometric field are matched. Maintaining t

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current constant, the pyrometer is ready for calibration or for temperature measurements. The instrument follows the law

$$\log\text{-tan}\ \varphi = a + \frac{b}{T} \qquad (48)$$

where φ is the angular reading of the analyzer, T the absolute temperature and a and b empirical constants. The relation between log-tan φ and $1/T$ is linear. Two calibration points serve to determine a and b, whence a table or plot may be made of φ vs. t deg. cent. $(T - 273)$. Frequent adjustments should be made of the current through the electric lamp necessary to obtain a match at the normal point when sighted on the amylacetate lamp. The electric lamp burns at a high temperature (about 1,800 deg. cent.) and consequently deteriorates rapidly. For the highest accuracy this adjustment should be made before and after a series of temperature readings; in industrial plants once a day or once a week will answer depending upon the amount of use. In the low range Wanner pyrometer the spectroscope is replaced by a red glass thus furnishing more light and still of sufficient purity in color.

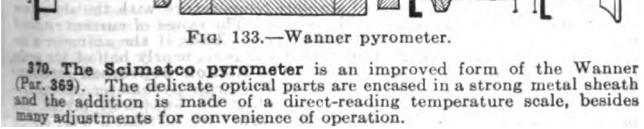


FIG. 133.—Wanner pyrometer.

370. The Scimatco pyrometer is an improved form of the Wanner (Par. 369). The delicate optical parts are encased in a strong metal sheath and the addition is made of a direct-reading temperature scale, besides many adjustments for convenience of operation.

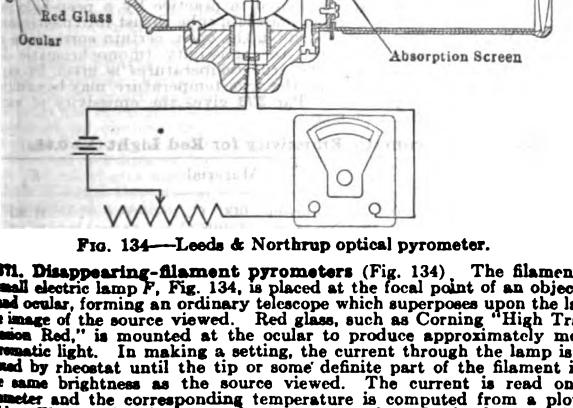


FIG. 134.—Leeds & Northrup optical pyrometer.

371. Disappearing-filament pyrometers (Fig. 134). The filament of a small electric lamp F, Fig. 134, is placed at the focal point of an objective L and ocular, forming an ordinary telescope which superposes upon the lamp the image of the source viewed. Red glass, such as Corning "High Transmission Red," is mounted at the ocular to produce approximately monochromatic light. In making a setting, the current through the lamp is adjusted by rheostat until the tip or some definite part of the filament is of the same brightness as the source viewed. The current is read on an ammeter and the corresponding temperature is computed from a plot or table. The relation between the current, i, through the lamp and the temperature t deg. cent., is of the form: $i = a + bt + ct^2$ where a, b, c, are constants requiring for their determination at least three standardization points.

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The lamps should not be operated at temperatures higher than 1500 d cent., on account of deterioration of the tungsten filament. If this te perature is not exceeded, the calibration of the lamp is good for hundre of hours of ordinary use. For higher temperatures, absorption glas *S*, Fig. 134, are placed between the lamp and the objective, or in front of t objective, to diminish the observed intensity of the source. The relati between the temperature of the source, T deg. abs., and the observed te perature, T_0 deg. abs., measured with the absorption glass interposed, is follows: $1/T - 1/T_0 = A$, where A is for most practical purposes a consta Usually the instrument is furnished with a table showing the relation l tween the current through the lamp and the temperature both with a without the absorption glass. If, however, this relation is not given the use of the absorption glass, it may be readily determined by measuri the constant A in the above formula. To do this, sight without the a sorption glass on a muffle or any uniformly heated furnace at 1200 deg. 1500 deg. cent. and observe the temperature T, in degrees absolute. Th with the absorption glass in place, match the filament again and observe what temperature, T_0, in degrees absolute, the current through the lar corresponds. The difference in the reciprocals of these two temperatu is the constant A, which is usually of the order of magnitude -0.00 This determination should be repeated several times and at several diff ent temperatures of the furnace. The separate values of A should n differ by more than 1 per cent. and the mean value is used for computi the relation between the observed absolute temperature with the absorpti glass and the true temperature of the source. The range of current requir is small, in general about 0.26 to 0.6 ampere. Thus, if the ammeter is c signed to give full-scale deflection with 0.6 ampere, nearly half of the sca from 0 to 0.26 ampere, is never used. The **Hickok depressed-zero am meter**, now furnished with the Leeds & Northrup pyrometer, meets th objection. The moving-coil system, including the supports, pivots, a pointer, may be adjusted relative to the magnet by turning a lever on t case of the instrument to one of two positions. In one position the pointer adjusted *on open circuit* so that it falls over the first graduation on t scale; this adjustment is similar to the ordinary zero adjustment on a ammeter. In the second, or working, position the zero is depressed fro the scale an amount equivalent to 0.26 ampere.

372. Emissivity corrections for optical pyrometers. Optical pyro eters will indicate true temperatures when sighted upon a black bod Black-body conditions are approximated in practice by a peep-hole in t side of a furnace or kiln, or a closed porcelain tube thrust into molten met or salts. When sighting upon objects in the open, certain corrections mu be applied. The relation between the emissivity (monochromatic ligh of a material and its observed and true temperatures is given by eq. 4 so that if the emissivity is known the true temperature may be comput from the observed temperature. Par **373** gives the emissivity of vario substances for red light ($\lambda = 0.65\mu$).

373. Monochromatic Emissivity for Red Light ($\lambda = 0.65\mu$)

Material	E_λ	Material	E_λ
Silver	0.07	Nichrome, 900° C	0.90
Gold, solid	0.13	Nichrome, 1200° C	0.80
Gold, liquid	0.22	Cuprous oxide	0.70
Platinum, solid	0.33	Iron oxide, 800° C	0.88
Platinum, liquid	0.38	Iron oxide, 1000° C	0.9[illegible]
Palladium, solid	0.33	Iron oxide, 1200° C	0.92
Palladium, liquid	0.37	Nickel oxide, 800° C	0.96
Copper, solid	0.11	Nickel oxide, 1300° C	0.85
Copper, liquid	0.15	Iron, solid and liquid	0.37
Tantalum, 1100° C	0.60	Nickel, solid and liquid	0.36
Tantalum, 2600° C	0.48	Iridium	0.30
Tungsten, 1000° C	0.46	Rhodium	0.30
Tungsten, 2000° C	0.43	Graphite powder (estimated)	0.95
Tungsten, 3000° C	0.41	Carbon	0.85

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374. Curve of emissivity corrections. Fig. 135 shows the corrections to apply to the pyrometer readings for a number of values of A, using s deg. cent. as abscissas and $(t-s)$ deg. cent. as ordinates. To obtain the true temperature corresponding to an observed temperature s deg. cent., add to s the value of the ordinate at the particular emissivity E_λ and abscissa s. As an example, let $E_\lambda = 0.30$, $s = 2{,}000$ deg. cent.; true temperature $= 2{,}000 + 320 = 2{,}320$ deg. cent.

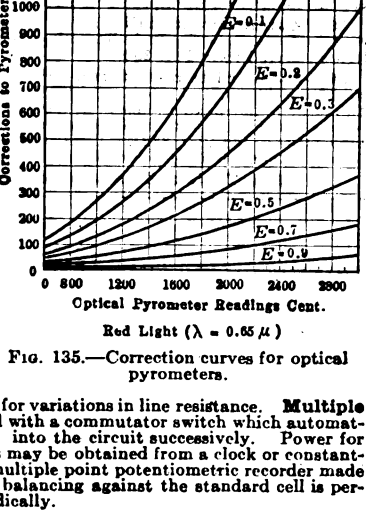


FIG. 135.—Correction curves for optical pyrometers.

375. Recording pyrometry. The following types of pyrometer may be made automatically recording. (1) Gas, saturated vapor, and liquid thermometers; (2) resistance thermometers; (3) radiation pyrometers; (4) thermoelectric pyrometers; of which the last has the greatest applicability. The usual type of curve required is temperature versus time, in which case the indicating instrument is equipped with a mechanism for periodically recording its indications upon a chart which moves with a uniform speed.

376. Types of recorder. The recorder may operate upon the galvanometric or potentiometric principle. In the former case its resistance should be high or some means should be provided for correcting for variations in line resistance. **Multiple point recorders** are constructed with a commutator switch which automatically connects various couples into the circuit successively. Power for operating the controlling devices may be obtained from a clock or constant-speed electric motor. In the multiple point potentiometric recorder made by Leeds & Northrup even the balancing against the standard cell is performed automatically and periodically.

377. Record charts. Three forms of record charts are used, roll, drum, and disk or circular charts. Multiple point records usually employ the roll chart. The roll chart may contain enough paper to last a month or more, while drum and circular charts are renewed every 24 hr. The lines of equal temperature on circular charts are represented by concentric circles and lines of equal time by arcs following the course of the galvanometer pointer. The distorted coordinates, however, are not confusing after some experience. Drum and roll charts may have rectangular coordinates but in some cases the lines of equal time are arcs of a circle with the length of the galvanometer pointer as a radius.

378. Transformation point indicators and recorders. The simplest and least accurate method of locating critical points is by means of a time-temperature curve, the critical region being indicated by a small flexure in the curve if the supply of heat is sufficiently regular. A more sensitive method employs a differential couple one junction of which is located in the sample under test and the other in a neutral body (one with no transformation points). A curve is obtained of the temperature of the sample versus temperature difference between the sample and neutral body when both are mounted together in a furnace the temperature of which is slowly increasing or decreasing. The critical region is shown by a sharp increase in this temperature difference. Both automatic and semi-automatic recorders are made for obtaining these curves directly, no computations or plotting of data being required.

379. Automatic alarm. The pyrometer indicator is fitted with two contacts on pivoted arms between which the meter pointer plays, thus

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closing a circuit which may operate a bell. The alarm in this form general operates for too great a part of the time unless the contacts a widely separated, when their usefulness is much lessened. The actio may be made intermittent, but even then the alarm is best employed on when there is danger to life or property.

380. Manual Signaling. Temperatures are measured in a centr station and instructions given to the furnace operator through pneumat tube service, by telephone or by colored lights. Signaling is usually accor plished by three lights at each furnace, different combinations representi certain departures from proper control.

381. Automatic signaling. A galvanometer or recorder may l equipped with a device including relays for operating the system of colore lights referred to in Par. 380.

382. Standard temperatures. From a consideration of determ natio made since 1900, and selecting only temperatures in the location of whi two or more independent observers have participated, and which are suitab for use as check points in physical and chemical operations, the followi table is presented (Par. 383). Temperatures above 1,550 deg. cent. are bas on $\alpha = 14{,}350$. Boiling-points are given for a pressure of 760 mm. Hg.

383. Table of Standard Temperatures; (deg. cent.)

Substance	Phenomenon	Tempera-ture
Hydrogen	Boiling	−252.7
Oxygen	Boiling	−182.9
Carbon dioxide	Sublimation (in inert liquid)	−78.5
Mercury	Freezing	−38.87
Water	Freezing	0
$Na_2SO_4+10H_2O$	Transformation to anhyd. salt	32.384
Water	Boiling	100
Naphthalene	Boiling	217.96
Tin	Freezing	231.85
Benzophenone	Boiling	305.90
Cadmium	Freezing	320.92
Lead	Freezing	327.4
Zinc	Freezing	419.4
Sulphur	Boiling	444.6
Antimony	Freezing	630.0
Aluminum	Freezing	658.7
71.9% Ag 28.1% Cu	Eutectic freeze	779
NaCl	Freezing	801
Silver	Freezing	960.5
Gold	Freezing	1063
Copper	Freezing	1083
Palladium	Freezing	1550
Platinum	Melting	1755
Alumina	Melting	2050
Tungsten	Melting	3400
Carbon arc	Pos. crater	3600
Sun	Surface	6000

Oxygen boiling-point*	$t = -182.9 + 0.013\,(p-760)$
Carbon dioxide, sublimation point	$t = -78.5 + 0.016\,(p-760)$
Water, boiling-point	$t = 100 + 0.037\,(p-760)$
Naphthalene, boiling-point	$t = 217.96 + 0.058\,(p-760)$
Benzophenone, boiling-point	$t = 305.9 + 0.063\,(p-760)$
Sulphur, boiling-point	$t = 444.6 + 0.0908(p-760) - 0.000047\,(p-760)^2$

Of the boiling substances, benzophenone and oxygen are the only ones the purity of which special attention need be given, but the metals used f freezing- or melting-points must be of the *highest* purity.

* p denotes pressure in mm. of Hg.

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384. Automatic temperature control. Automatic control at low temperatures, or "thermostating," is usually obtained by means of the movement of bimetallic springs or the thermal expansion of rods or fluid columns. For higher temperatures thermoelectric instruments are employed, the principle of operation being similar to that used in automatic signaling. Instead of operating lights, however, the relays control electromagnetic valves for oil or gas, or switches in the case of electrical heating. Automatic control is complicated by the interrelation of such factors as thermal lag and the magnitude of the corrective changes in heat supply during each period of reversal. The sensitivity of the control instrument determines the range of temperature which must be covered by the couple during each reversal of the valve or switch. The range of temperature covered by the source of heat is greater than this, the magnitude being affected by the type of furnace, method of firing, and location of the couple. For closest regulation, which is best accomplished electrically, the couple must be very near if not in contact with the heater. In electrical heating the current is changed by opening and closing a switch which shunts a portion of the controlling resistance or changes series and parallel connections of the heater or transformer. In gas and oil heating the supply pipe is by-passed and the control valve is located in the shunting line.

HEAT CONDUCTIVITY

385. Heat Conductivity. Three processes exist by means of which heat may be transferred from one body to another, by radiation, by convection and by conduction. All of these factors enter into the computation of the heat losses from a furnace, but frequently the loss by convection and radiation may be made small or negligible in comparison with the loss by conduction. The quantity of heat which flows through a plate of area A and thickness e in a time t is expressed,

$$Q = k(\theta_1 - \theta_2).A\ t/e \qquad (49)$$

where θ_1 and θ_2 are the temperatures upon each side of the plate (a plate theoretically infinite in extent) and k is known as the **thermal conductivity.** k is defined by the quantity of heat which flows per unit time through unit area of a plate of unit thickness, having unit difference of temperature between its faces. Numerically k is usually expressed as the quantity of heat in small calories which is transmitted per second through a plate 1 cm. thick, per square centimeter of its surface, when the difference in temperature between the two faces is 1 deg. cent. Q then refers to g-cal., θ to deg. centigrade, A to square centimeters and t to seconds. k is found to vary with the temperature of the plate and is expressed approximately by the equation

$$k_t = k_o(1 + \alpha t) \qquad (50)$$

where t is the temperature centigrade and α a constant. As an example be it required to find the quantity of heat lost per hour by conduction through a section 100 cm. by 100 cm. of a fire-brick furnace wall 20 cm. thick, the conductivity being 0.00028 cal./(cm.-sec.-degree) and constant with temperature, the inside temperature of the furnace being 1,500 deg. cent. and the outside 300 deg. cent.

$$Q = 0.00028\ \frac{1{,}500 - 300}{20}\ 100 \times 100 \times 3{,}600 = 605{,}000\ \text{g.-cal.}$$

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FUEL AND GAS ANALYSIS

BY F. MALCOLM FARMER, M.E.

387. The purpose of this section is to indicate very briefly the more important features in connection with fuel and gas analysis. For further information, the reader is referred to the numerous publications on fuel and gas analysis. See Par. **402.**

388. Coal for steaming or producer purposes is usually subjected only to a proximate or engineering analysis, which includes the determination of the heating value and the percentages by weight of moisture, fixed carbon, volatile matter, sulphur and ash. When a complete or ultimate analysis is made, the components of the volatile matter are also determined.

389. The details of manipulation in coal analyses have a marked effect on the result and since many of the determinations are made in a manner more or less arbitrary, care should be taken to conform to **standard** practice. The accepted standard practice is that recommended by the American Society for Testing Materials in their Specification No. D22–16 entitled, "Standard Methods for Laboratory Sampling and Analysis of Coal." It gives complete details for the preparation of the sample in the laboratory and for making the various determinations indicated in the preceding paragraph.

390. The sampling of coal is of the utmost importance. The greatest care is necessary in order to obtain a sample which is truly representative of all of the coal in the lot which the sample is to represent. In general, a large sample of 500 to 1000 lb. should be made up of small quantities taken from various parts of the entire lot. This is gradually reduced to a 30-lb. sample about pea size, by crushing, mixing and quartering.*

391. Heating values of fuels are determined with **calorimeters,** or instruments in which the heat evolved by the combustion of a sample of the fuel is absorbed by water, the weight and rise in temperature of which are observed. There are two general classes, the non-continuous class in which only a small quantity of the fuel (solid or liquid) is burned at one time, and the continuous class where the fuel (liquid or gaseous) flows continuously through the calorimeter.

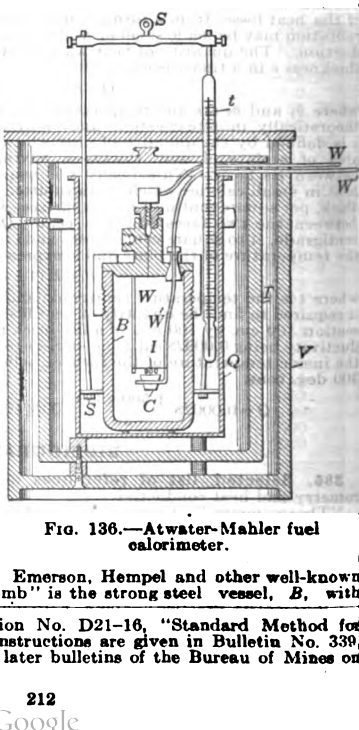


FIG. 136.—Atwater-Mahler fuel calorimeter.

392. The Berthelot or bomb type calorimeter of the **non-continuous class** is most generally used for high-grade commercial work. Fig. 136 shows the arrangement of parts in an **Atwater-Mahler calorimeter,** which is similar to the Mahler, Emerson, Hempel and other well-known **bomb calorimeters.** The "bomb" is the strong steel vessel, *B*, with

* See A. S. T. M. Specification No. D21–16, "Standard Method for Sampling of Coal." Excellent instructions are given in Bulletin No. 339, U. S. Geological Survey, and in later bulletins of the Bureau of Mines on coal sampling.

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closely fitting screw-top and lined with platinum, gold, nickel, enamel or other non-corrosive material. A valve is provided at the top for supplying oxygen. The sample is placed in the crucible, *C*, and ignited by the very fine iron wire, *I*, which is heated to incandescence by an electric current through *W* and *W'*. The bomb is placed in the calorimeter vessel proper, *Q*, which is filled with water. Heat insulation is provided by placing the calorimeter in two other vessels, *T* and *V*, separated by air spaces. The water is agitated by the stirrer, *S*, and its temperature measured with a thermometer, *t*.

The procedure in operation is briefly as follows: About 1 g. of coal is carefully weighed in the crucible, which is placed in the bomb with the fine iron wire carefully arranged in contact with the coal. After the top is screwed on the bomb is filled with oxygen at a pressure of 300 lb. to 450 lb. per sq. in., and placed in the calorimeter tank, which contains a known weight of water. After the initial "radiation" rate is obtained, the specimens ignited and the rise in temperature of the water observed. When the rate of change of temperature becomes constant, the final "radiation" rate is obtained. The heating value per pound is calculated from the weight of the specimen, the weight of the water and the rise in temperature. Correction is made for the heat capacity of the calorimeter ("water equivalent"), the "radiation" during the combustion interval, the heat from the electric energy used in heating the wire and the heat of combustion of the latter. The temperature range is only a few degrees centigrade and is usually measured with differential mercury thermometers, read to 0.001 deg. with the aid of a microscope.

393. The essential details of procedure for a proximate analysis are as follows: (1) The whole sample is placed in a shallow pan and air-dried in a special oven at 10 deg. or 15 deg. cent. above room temperature until the weight is practically constant (from 2 to 4 hr.) The loss in weight is the **surface moisture** or **"air-dry" loss.** The sample is then ground in a coffee mill until it will pass through a 20-mesh sieve;* it is next quartered and then about 100 g. are ground in a mortar or ball mill to 80 or 100 mesh.

(2) **Total moisture** is obtained by heating 1 g. of the final sample in an open porcelain or platinum crucible in an oven at 104 to 107 deg. cent., and noting the loss in weight.

(3) **Volatile matter** is obtained by heating 1 g. in a special, covered platinum crucible at a bright red heat in a Bunsen flame for 7 min. The total loss in weight is equal to the volatile matter plus the moisture.

(4) **Ash** is determined by burning 1 g. of the sample in an open crucible until the weight is constant (1 to 2 hr.). The highest temperature of the Bunsen flame is utilized. Sometimes a small stream of oxygen at low pressure is injected into the crucible to hasten combustion.

(5) **Fixed carbon** is determined by calculation, that is, fixed carbon = 100 − (moisture + volatile matter + ash), all expressed in per cent.

(6) **Sulphur** is determined as follows: 1 g. of the coal is mixed with suitable chemicals (such as magnesium oxide and sodium carbonate) and burned. The residue is extracted with water, filtered, and the sulphur precipitated from the solution with barium chloride, coming down as barium sulphate. From the weight of this precipitate, the percentage of sulphur in the original sample is calculated.

394. The Junker calorimeter is the best known example of the continuous class. It is used extensively for gas fuels and can also be used for liquid fuels. Fig. 137 shows the calorimeter set up for gas testing. The gas flows through the meter *M* and a pressure regulator *R* to a special Bunsen burner inside of the calorimeter *C*. The combustion chamber is surrounded by a chamber through which water flows at a constant rate. The heating value in B.t.u. per cubic foot of gas is calculated from the rate of gas consumption, rate of flow of the water and the difference between the average inlet and average outlet water temperatures. For liquid fuels, a weighing device and a special burner are provided.

395. Other types of calorimeters of the **discontinuous class** differ essentially from the Berthelot only in the method of supplying the oxygen. In calorimeters of the Carpenter and the Favre and Silberman type, oxygen

*20 clear spaces per linear inch.

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gas is supplied at atmospheric pressure. In instruments of the Parr class, the oxygen is supplied by chemicals with which the sample is mixed.

396. Fuel oils are, in addition to the foregoing, Par. **394**, frequently tested for **flash-point**, or temperature where the vapor given off will ig-

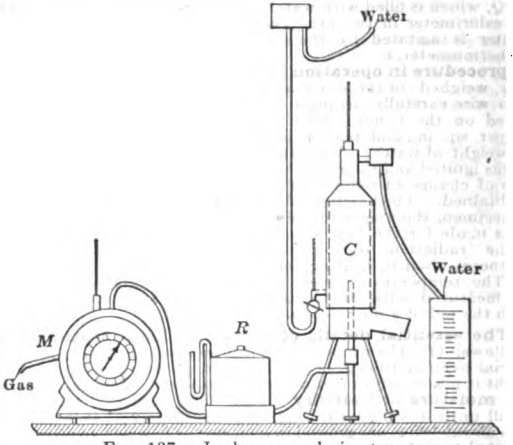


FIG. 137.—Junker gas calorimeter.

nite but will not continue to burn; **fire-point**, or temperature wher combustion will continue if the vapors are ignited; **viscosity**; **chill-point** or congealing temperature; per cent. of asphaltum.

397. Reports of proximate analyses and heating value (in B.t.u. pe pound) usually give the results calculated on at least two bases, "as received" and "**dry.**" The former are of most interest to the users of the fuel, but the results must be reduced to the latter basis when comparisons are to be made.

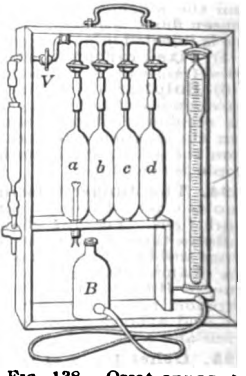


FIG. 138.—Orsat apparat

398. Fuel or illuminating gases are analyzed for the following **components in per cent. by volume**; **carbon dioxide** (CO_2), **carbon monoxide** (CO), **oxygen** (O_2), **methane** (CH_4), **ethylene** (C_2H_4), **hydrogen** (H_2) and **nitrogen** (N). CO, CO_2, O_2 and C_2H_4 are usually determined by passing a known volume of the gas through a series of reagents, one at a time, each of which will absorb one, and only one, of the components. The diminution of the volume is noted after each absorption. H_2 and CH_4 are obtained by combustion in a glass tube with a known volume of air, the products of combustion being measured by absorption as in the case of the other constituents, and the original volume calculated. N is obtained by difference.

399. Orsat apparatus. The various forms of apparatus which employ the **absorption method** are based on the principle of the Orsat apparatus sho in Fig. 138. A given quantity of gas, usually 100 c.c., is drawn into

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measuring tube, *T*, by means of the water bottle, *B*, and carefully measured. The gas is then forced into the CO_2 reagent bottle, *d*, drawn back into *T* and the decrease in volume noted. The process is repeated with each of the tubes, *c*, *b* and *a*, giving the percentages of O_2, CO, and H_2 respectively. The usual **reagents** are caustic potash solution for CO_2, ammoniacal cuprous chloride solution for CO and alkaline pyrogallic acid solution for O_2, H_2 being obtained by combustion.

399. Flue gases are analysed for **carbon dioxide** (CO_2), **carbon monoxide** (CO), **oxygen** (O_2), **hydrogen** (H_2) and **nitrogen** (N), in the manner indicated for fuel or illuminating gas.

401. CO_2 recorders are instruments which automatically and continuously remove samples of flue gas and indicate with a pointer or record on a clock-driven chart the percentage of CO_2 in each sample. Various principles are employed, among which are the variation in the refraction index with the percentage of CO_2, the variation in density compared with air as a standard, and the variation in the position of a float with the volume remaining after the CO_2 has been removed with caustic potash, the usual reagent.

403. Selected list of reference literature on fuel and gas analysis.

Lewes, V. B.—"Liquid and Gaseous Fuels." D. Van Nostrand Co., New York.

Gill, A. H.—"Gas and Fuel Analysis for Engineers." John Wiley & Sons, New York.

Kershaw, J. B. C.—"The Calorific Value of Fuels." D. Van Nostrand Co., New York.

Sonnenberger, E. E.—"Coal, Its Composition, Analysis, Utilization and Valuation." McGraw-Hill Book Co., New York.

Moyer, J. A.—"Purchasing Coal by Specification." *Jour.* Engineering Society of Pennsylvania, Aug., 1913.

Fuel Technology Publications, U. S. Bureau of Mines (Formerly U. S. Geological Survey).

Bulletin No. 12. Apparatus and Methods for the Sampling and Analysis of Furnace Gases, 1911.

Bulletin No. 23. Steaming Tests of Coal, 1912.

Bulletin No. 63. Sampling Coal Deliveries and Types of Government Specifications, 1913.

Technical Paper 3. Specifications for Fuel Oil for the Government, 1911.

Technical Paper 8. Methods of Analysing Coal and Coke, 1912.

Technical Paper 26. Methods of Determining Sulphur in Fuels, Especially Petroleum Products, 1912.

Technical Paper 49. Flash-point of Oils, Methods and Apparatus, 1913.

Bulletins, University of Illinois Experiment Station:

No. 15. How to Burn Illinois Coal without Smoke, 1908.

No. 31. Fuel Tests with House Heating Boilers, 1909.

No. 37. Unit Coal and Composition of Coal Ash, 1909.

No. 38. Weathering of Coal, 1909.

No. 46. Spontaneous Combustion of Coal, 1911.

WATER, GAS, AIR AND STEAM METERS

BY REGINALD J. S. PIGOTT

WATER METERS

404. Classification. Water meters are of three classes: weighing, volumetric and kinematic.

404. Water weighers are not affected by variations in temperature and allow, approximately, 2 per cent. error. All weighers must be fed with a gravity flow. The various methods employed by concerns manufacturing water weighers are described in Par. **405** to **408**.

405. Worthington weigher. In this device two counterweights are mounted on trunnions, water flowing into one tank while the other empties. As the water rises the centre of gravity of the tank and water is shifted, finally reaching a point where the tank upsets and empties. This movement automatically throws the water deflector over to fill the other tank. See Fig. 139. This device will, of course, weigh only in units corresponding to the weight contained in one tankful; the number of trips of the tanks being auto-

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matically taken by a counter and multiplied by the tank unit weight. The accuracy approximates 2 per cent. See Par. **404.**

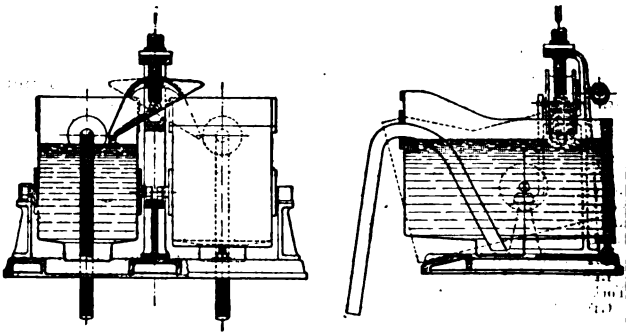


FIG. 139.—Worthington recording liquid weigher.

406. The Richardson weigher, Fig. 140, uses a single weighing tank mounted on knife-edged scale beams directly counterbalanced. The overbalancing of the weighing tank trips the feed valve from the upper reservoir and opens the discharge. By a system utilising two toggles and dead-centres, the upper valve does not open till the outlet valve is again entirely closed. See Par. **404.**

407. The Wilcox weigher operates as a single tank with a syphon outlet. The bell float and standpipe (which is open top and bottom), are down normally, so that the standpipe seals the opening in the diaphragm between upper and lower tanks. Water accumulates in the upper section until it overflows the top of the standpipe and runs down into the lower compartment, trapping air in the bell and inner legs of the two siphon, and raising the bell. As the water rises, the trapped air is compressed until finally it breaks through the trip seal and starts the main siphon. The release of air pressure allows the bell and standpipe to drop, and the cycle begins again. See Par. **404.**

408. Volumetric meters include measuring-tank meters (other than weighers), piston meters and disc meters. Variations in temperature affect all these types, so that they must be calibrated for the average temperature on which they are to be used. Accuracy of piston and disc meters should be 1.0 to 1.5 per cent. average error, provided they are properly used and not worn. Wear of piston meters or disc meters, causing leakage, may increase the percentage of average error to 5 or 10 per cent. The various types of volumetric meters are described in Par. **410 to 412.**

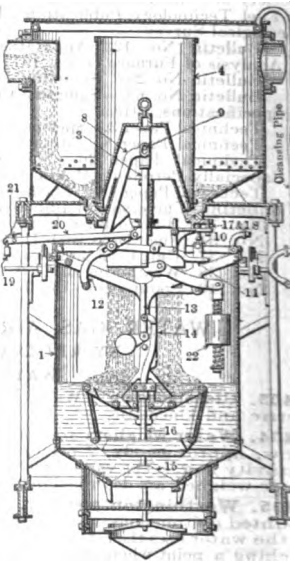


FIG. 140.—Richardson weigher

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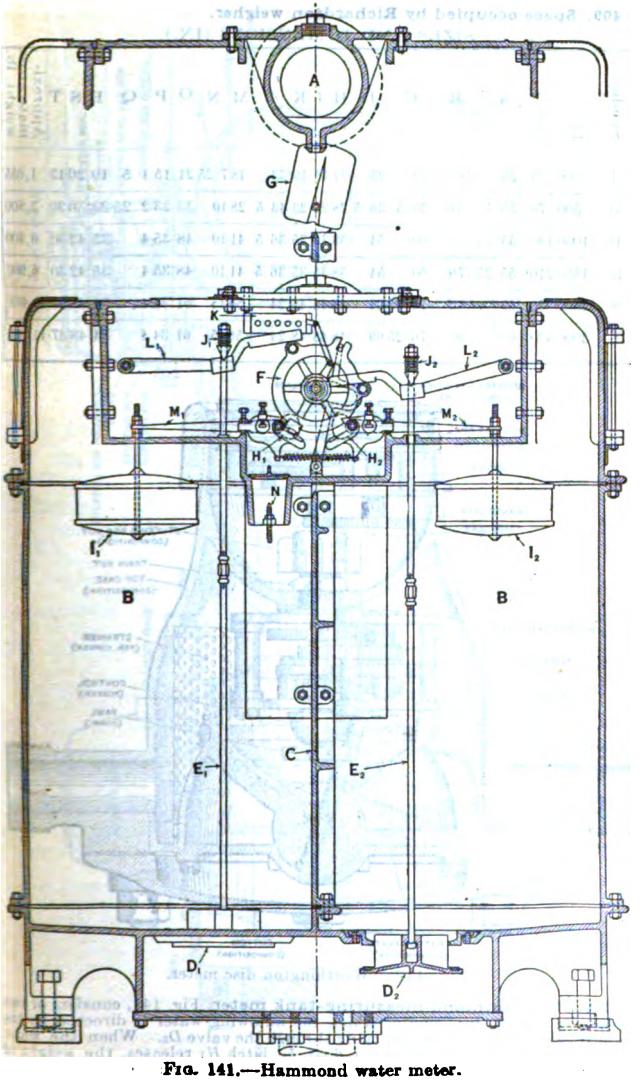


Fig. 141.—Hammond water meter.

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409. Space occupied by Richardson weigher.

SIZES AND DIMENSIONS (IN.)

Symbol	Lb.	Gal.	A	B	C	D	H	J	K	L	M	N	O	P	Q	R	S	T	Approximate gross weight, lb.
J	200	25	25	38.5	22	25	21	15	19	33	18	7.25	21	15	1.5	19	20	13	1,065
M	500	70	36.5	54	30.5	36.5	28	23	23	43.5	28	10	32	23	2.25	23	30	20	2,800
P	1000	140	55.25	76	60	54	38	35	35	36.5	41	10	48	35	4	35	42	30	6,400
R	1500	210	55.25	76	60	54	38	35	35	36.5	41	10	48	35	4	35	42	30	6,900
S	2500	350	69	96	76.25	69	48	48	48	24	56	15	61	34	4	34	48	37	10,400
T	3000	420	69	96	76.25	69	48	48	48	24	56	15	61	34	4	34	48	37	11,000

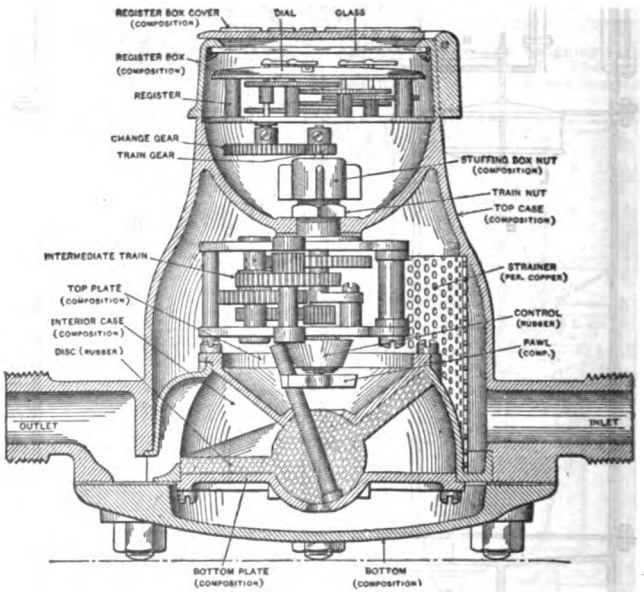


FIG. 142.—Worthington disc meter.

410. The Hammond measuring-tank meter, Fig. 141, consists of two tanks, B_1 and B_2, into one of which the inflowing water is directed by the baffle G, while the other is emptying through the valve D_2. When the water level in B_1 rises high enough to lift float I_1, latch H_1 releases, the weight of water on valve D_1 throws the wrist plate over, opening D_1 and closing D_2, and

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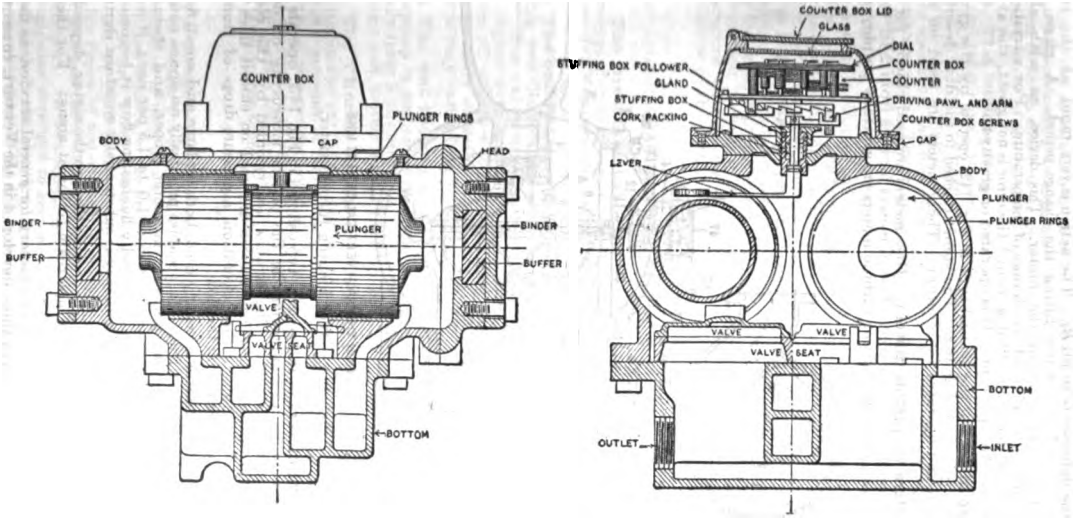


FIG. 143.—Duplex piston meter.

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changing the deflector G to fill B_2. The action is very rapid at the release period, preventing loss of water during the change period. A gage, N, is included for accurately setting the meter. This device, as with all the volumetric meters, is affected by change of temperature. For variations of approximately 50 deg. fahr. (28 deg. cent.) the error is not great, the average being 2 per cent. to 3 per cent. It is operated on gravity flow.

411. Disc meters of the general type in Fig. 142, operate by the gyration of a disc in a spherical chamber. The stem attached to the disc describes a circular path and operates the counter. These meters are used on closed lines under pressure.

Disc meters vs. piston meters. Disc meters are used chiefly for small lines, up to about 3 in. diameter. Piston meters for sizes from 2 in. to 8 in. For larger flows, tank, Venturi or turbine meters are generally employed.

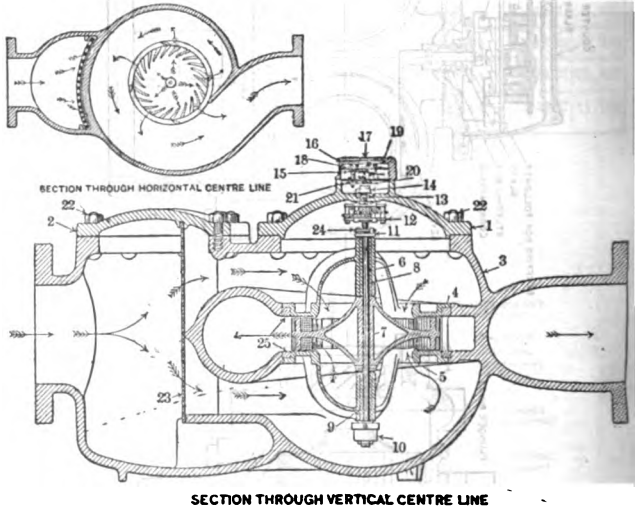


FIG. 144.—Worthington turbine meter.

412. Piston meters of the general type shown in Fig. 143, operate like a duplex steam pump, the movement of the pistons measuring off definite volumes of water per stroke. The strokes are recorded by the counters usually in units of cubic feet. These meters are used on closed lines under pressure, and necessitate, for their operation, a pressure drop of from 2 to 6 lb. per sq. in., depending on the flow.

413. The Venturi meter is widely used, both for large and small flow, on pumping service and boiler feed. It occupies practically no space outside of the pipe line; has no moving parts in the meter proper, and operates on closed pressure lines. The accuracy is from 1.0 to 1.5 per cent. if used on reasonably steady flow. If used on rapidly fluctuating flow it becomes very inaccurate. If kept clean, the accuracy is substantially constant during the life of the meter.

A slight pressure drop, 0.25 to 3 lb., occurs through the meter, depending in amount on the flow and ratio of upstream to throat areas. For theory of the Venturi tube, see Sec. 10.

414. The Pitot meter is not satisfactory for general service, as the head differences are much less than those developed in the Venturi, consequently

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the registering apparatus is much more delicate and sensitive to leakage in the pressure lines leading from the main to the recording instrument. It is also very sensitive to eddies in the pipe lines in which the Pitot tube is inserted. For the theory of the Pitot tube, see Sec. 10.

415. The turbine meter, Fig. 144, is used to some extent for large-size lines and large flow. It operates like a hydraulic turbine, and as the meter opposes practically no friction or pressure loss to flow, the speed of the meter is substantially proportional to the flow. It is called a "velocity meter," but strictly speaking, this meter is volumetric; it is affected in accuracy by temperature changes. The accuracy is practically the same as the weighers and tank meters (**Par. 404**).

416. Weirs, usually of the V-notch type, are in considerable use, in connection with indicating and recording mechanisms for water measurement. (See Sec. 10.) In the **Lea type**, a float in a chamber above the weir, operates a grooved drum in such a fashion that the recording and integrating apparatus move over equal increments of space for equal increments of flow.

In the **Hoppes type**, a conoidal float is suspended by a coil spring, and is so shaped that the descent of the float by the weight of water forced over by the rise of the weir, is proportioned to the flow. Very good accuracy is claimed for these weir meters, from 0.5 to 1.3 per cent. over all ranges of flow. Temperature changes are approximately compensated in both types, by the behavior of the float and the conoidal chamber respectively.

GAS METERS AND AIR METERS

417. The meters available for gas and air measurement are: (a) bellows-type, for low pressure chiefly; (b) Thomas electric, for high or low pressure; (c) Venturi-tube, Pitot tube, and disc orifice types for high or low pressures; (d) wet types for low pressure; (e) rotaries.

418. The bellows type "dry" meter has usually a pair of leather bellows operating two diaphragms, after the manner of a piston in a reciprocating engine. The valve operation is exactly like that of a two-cylinder double acting engine with quartering cranks. The movement of the diaphragms measures off volumes of gas. The pressure and the temperature must be kept reasonably constant, as the accuracy of the meter is affected by both. The error may range from 3 per cent. "slow" to 2 per cent. "fast."

419. The wet meter is now used chiefly for large gas-works service, and its operation is somewhat like that of a rotary engine. The average error is usually from 3 per cent. slow to 2 per cent. fast. The obtainable accuracy with large wet meters is within 0.1 per cent.

420. The Thomas electric gas meter consists of an electric resistance heater coil in the gas main, a wattmeter and two screen-resistance thermometers. An amount of current is passed through the heater such that the difference of temperature of the gas before and after passing the heater is a definite amount as measured by the screen thermometers, which automatically average the temperature.

The relation between the temperature, watts input and flow is then

$$W = \frac{0.05686\,E}{ts} \qquad \text{(lb. gas per min.)} \qquad (51)$$

where t = temperature difference, inlet and outlet, deg. fahr.; s = specific heat at constant pressure of air or gas measured; E = watts input. The Thomas meter is used as a substitute for the huge wet meters formerly employed at gas houses for the main-flow measurement. Its accuracy is higher than that of any other device now in use for air or gas flow, the error being from ± 0.05 to ± 0.2 per cent. In small sizes it is too expensive to compete with other types of meter, but in large sizes it is much less expensive in proportion, and has the additional advantages of indicating and recording as well as integrating. In commercial service it is generally equipped with an automatic regulator arranged to keep a constant temperature difference between inlet and outlet; the electric instruments can then be graduated directly in pounds or cubic feet, as the flow is directly proportional to the watts input.

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421. Venturi meters are in some use for large gas-flow measurements; the device is accurate, but the formula for its use is complicated.

The formula for air and gas service is

$$W = CA_2 \left(\frac{P_2}{P_1}\right)^{\frac{1}{\gamma}} \sqrt{2g \frac{\gamma}{\gamma-1} P_1 \delta_1 \left[\frac{1 - \left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}}}{1 - \left(\frac{A_2}{A_1}\right)^2 \left(\frac{P_2}{P_1}\right)^{\frac{2}{\gamma}}}\right]}$$

(lb. gas or air per sec.) (52)

Where A = upstream area, sq. ft.; A_2 = throat area, sq. ft.; P = upstream pressure, lb. per sq. ft.; P_2 = throat pressure, lb. per sq. ft.; γ = ratio sp. heat at constant pressure to sp. heat at constant volume; = 1.408 for air = 1.266 for natural gas; δ_1 = density, lb. per cu. ft. at upstream section C = 0.98, coefficient of flow; g = gravitation constant, 32.2.

For differences of pressure less than 20 in. of water, the hydraulic formula may be employed without error in excess of 1 per cent.

$$Q = 18.3 \frac{A_2}{\sqrt{1 - \left(\frac{A_2}{A_1}\right)^2}} \left(\frac{h\left(\frac{P_2}{P_1}\right)^{\frac{1}{\gamma}}}{\delta_1}\right)^{\frac{1}{2}}$$ (cu. ft. per sec.) (53)

where Q = cu. ft. per sec. ($= W/\delta_1$); h = difference of pressure, upstream and throat in in. of water [$= (P_1 - P_2)(12/62.35)$].

422. The Pitot-tube formula for gas and air

$$Q = 218.44 E d^2 \frac{T_s}{P_s} \sqrt{\frac{hP}{TG}}$$ (cu. ft. gas or air per hr.) (54)

where E = flow factor of the tube expressed as a decimal; d = internal diam. of tube (in.); T_s = absolute fahr. temperature of measurement base; P = absolute pressure of measurement base, lb. per sq. in.; G = sp. grav. of gas referred to air; if air is measured, $G = 1$; P = absolute static pressure of flowing gas in meter, lb. per sq. in.; T = absolute temperature fahr. of flowing gas; h = velocity head of flowing gas (in. of water); Q = cu. ft. of gas per hr. at T and P.

The value of E is 0.8530 for smooth tubes, 2-in. to 5-in. diameter, with the Pitot tube placed exactly in the centre of the pipe. The velocity is a maximum at the centre of a pipe, decreasing to a minimum at the pipe surface. This accounts for the fact that E is less than unity when the Pitot tube is at the centre of the pipe. The coefficient of flow for the Venturi meter approximates from 0.97 to 0.98 for properly designed meters.

423. Thin disc orifices operate on the same formula as the Venturi meter, except that the coefficient of discharge C varies with the ratio of orifice diameter to pipe diameter. The simplified formula allowing for the orifice ratio is

$$W = 360 \times d^2 \times C \times \sqrt{h_w y}$$ (55)

Where W equals pounds per hour, d equals the diameter of the orifice in inches, C equals coefficient of discharge, h_q equals the differential head in inches of the fluid at the conditions of measurement, y equals the density. Coefficient C has the following values:

Ratio of orifice diameter to pipe diameter	Value of coefficient
0.10	0.598
0.20	0.600
0.30	0.604
0.40	0.612
0.50	0.627
0.60	0.657
0.70	0.707

These coefficients are affected to some extent by the positions of the pipe connections up-stream and down-stream for obtaining the differential pressure.

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STEAM METERS

424. Steam meters. Most of the steam-flow meters such as the St. John, Bailey, Republic, and General Electric, etc., can be used on **compressed-air service** if desired. See Par. **423.** Steam meters are divided into area meters (Par. **425** and **426**) and so-called flow meters (Par. **427** and **428**). Pressure and quality variation affect the accuracy of all area and flow meters, so that the meters are only correct for the calibration conditions of pressure and quality, unless fitted with compensating devices.

425. "Area" steam meters. In this class are those in which a disc or cup partially closes an opening through which steam is passing. The shape of the passage or of the cup is so arranged that as it rises from zero position, the free area for passage of steam is increased. As demand for steam is increased, the increase of pressure drop past the disc or cup, causes it to move further up the passage, enlarging the area till the pressure drop is reduced and the disc again in equilibrium. The movement of the disc is communicated to an indicator and chart graduated in lb. per hr. flow. The passage is so designed that the movement of the disc or cup is directly proportional to the flow, giving an equal increment reading.

426. The St. John meter is an example of the area type. It has a conical plug floating vertically in a circular seat. As the stream flow is increased, the plug rises, exposing more area for flow between plug and seat. As the weight of the plug and stem is the only load, the pressure difference is constant.

427. Pressure indicating devices for use with velocity steam meters. All the flow meters (Venturi, Pitot and orifice types), require some form of sensitive differential gage which will accurately measure a small difference between two high initial pressures.

The simplest indicating apparatus consists of a glass water—or mercury—U tube. To this class belong the Gebhardt, Gehre and General Electric testing type.

428. The Gebhardt steam meter, Fig. 146 is given as an example of the gage-glass type of velocity meter and reads directly by a water column on a chart graduated in lb. per min. or per hr., and for a complete range of pressures. To read the meter correctly, it is necessary to know the pressures and quality. By means of a small condensing chamber this meter is made suitable for use with superheated steam. Accuracy of the Gebhardt meter (also the G. E. type TS₂ and Gehre) is ±1 per cent. on careful handling, but more usually ±1.5 to 2 per cent. in ordinary service without constant pressure and quality check.

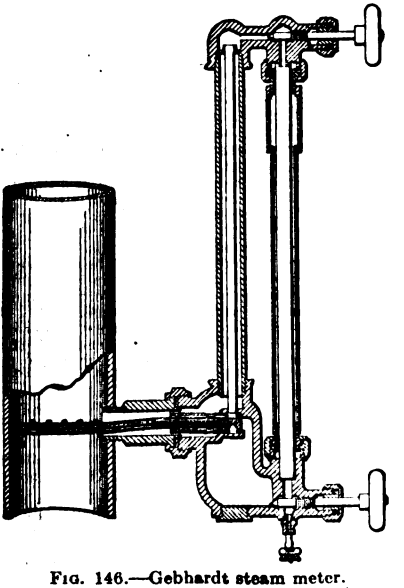


FIG. 146.—Gebhardt steam meter.

The Thomas electric meter can be used for measuring steam very accurately, but it cannot be commercially employed as the amount of current required becomes excessive (on account of the high specific heat of steam) and especially for wet steam where moisture must be evaporated.

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429. Steam-meter costs. At the present time there are available a least three meters, suitable for general testing, and for the boiler or engin room as permanent instruments. Of the recording instruments, while on or two are satisfactory in operation, the price of all is still too high fo general adoption. There is nothing about these instruments which shoul prevent their manufacture and sale in the same manner and at about th same price as high-grade recording gages, provided their construction standardized and put on a production basis.

PRECISION OF MEASUREMENTS

BY WILLIAM J. DRISKO

430. Classification of measurements. For convenience of treatmer all measurements are classified as either direct or indirect. **A direc measurement** consists in determining the **numeric** which expresses th magnitude of the quantity in terms of some arbitrary unit. Thus lengt determined by means of a graduated scale, time by a clock, volume of a liqui by a graduated flask, etc., are illustrations.

Measurements are indirect when the numeric is obtained by som computation making use of some functional relation expressed by a formul *e.g.*, the density of a sphere expressed by the relation $d = M/(\frac{1}{6}\pi D^3)$, wher M is the mass obtained by means of an equal-arm balance and D the diam eter measured by a micrometer caliper; or the horse power of an engin h.p. = p.l.a.n./33,000, where p is the mean-effective pressure found by mea urement, l the length of stroke, a the area of the piston found by measurin its diameter and n the number of strokes per minute found by countin them. In general these expressions take the form,

$$X = F(a, b, c \ldots \quad A, B, C \ldots)$$

where a b, c . . . represent measured quantities, while A, B, C . . . rep resent constants (like 33,000 and π in the above formulæ) and F repr sents that there is some functional relation between measurements, constan and the indirectly measured quantity X.

431. Every measurement has a definite precision. Thus the leng of a building might be reliable to the nearest quarter inch, the current in certain circuit to the nearest tenth of an ampere, or the time of vibration a pendulum to the nearest hundredth of a second. To determine th reliability it is necessary to make a very careful study of all the instrumen used, the care with which they are made, graduated, calibrated, adjuste for change of temperature or of position, etc., etc. It furthermore is nece sary to know not only the skill of the observer, but also whether any consta errors may be due to his "personal equation." If for instance one desir to calibrate a voltmeter at 110 volts by means of a standard Weston ce the following points must be considered: How closely must the electr motive force at standard temperature be determined? How closely must th temperature coefficient be determined? If the temperature of the cell whe used is determined by means of a mercury thermometer, how closely mu the thermometer be calibrated and read? How closely must the resistan of the voltmeter be known and is it necessary to take any precautions r garding its temperature; and lastly, what must be the precision of the variab resistance used for the balance? After an examination of all these probab sources of error the final question is, What is the most probable value of th combined effect of all these separate deviations or errors? (See Par. 1–6.)

432. The general problem. Given the functional relation,

$$X = F(a, b, c \ldots) \qquad (5$$

the problem in general is as follows: First case if a, b, c . . . can b measured each with a definite degree of precision, what is the best repr sentative value of the resultant precision in X? Second case: if it is d sired to determine X to a certain definite precision, how precisely mu each of the components be measured so that the combined effect of all th deviations may not produce a resultant deviation in X greater than th assigned limit?

Unless it is possible to assign some numerical estimate to the precisio attained in determining any measured quantity, X, the result is of litt practical value. Hours of valuable time are often wasted in determinin some unimportant component of an indirect measurement with excessiv precision, while at the other extreme we often find final results absolute

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worthless as the result of failure to measure some important component with the necessary precision.

433. Determination of precision in final result with known precision in the measured components. Referring to Eq. 56, let δ_a, δ_b, δ_c . . . be the numerical deviations or precision measures of the direct measurements a, b, c . . . ; Δ_a, Δ_b, Δ_c be the deviations in X due to the deviations in the separate components, and Δ the combined effect of the separate effects Δ_a, Δ_b, Δ_c . . . . Then Δ/X is the fractional deviation or precision measure of X and δ_a/a, δ_b/b, δ_c/c . . are the fractional deviations of the components a, b, c . . . and 100 times the fractional deviation is the percentage deviation. We first find the separate effect of each of these deviations δ_a, δ_b, δ_c . . . on X and then find the combined effect of these separate effects. The change in X due to a slight change in a (b, c . . . remaining constant) is found by differentiating the function with respect to a, *i.e.*,

$$\Delta_a = \frac{\partial X}{\partial a}\,\delta a \tag{57}$$

and a similar slight change in any component k would give

$$\Delta_k = \frac{\partial X}{\partial k}\delta k \tag{58}$$

It can be shown that the most probable value of the resultant effect, Δ, of the separate effects, Δ_a, Δ_b, Δ_c . . . is

$$\Delta = \sqrt{\Delta_a^2 + \Delta_b^2 + \Delta_c^2 + \ldots} \tag{59}$$

Example. The value of the acceleration due to gravity is to be determined by means of a pendulum whose length and time of vibration are to be measured and used in the formula $g = \pi^2 l/t^2$. Here X is g, a is l, b is t and π is a constant. Measurements gave $l = 101.42$ cm., reliable to 0.05 cm. and $= 1.0094$ sec., reliable to 0.0008 sec. How precise is the value of g when computed from this data? Differentiating with respect to l, we have, $\Delta_l = \pi^2\delta_l/t^2 = 9.9/1.0 \times 0.05 = 0.50$ cm. per sec. per sec. Differentiating with respect to t we get, $\Delta_t = -\pi^2 l \times 2 \times \delta_t/t^3 = 9.9 \times 100 \times 2 \times 0.0008/1.0 = 1.6$ cm. per sec. per sec. This means that a deviation of 0.05 cm. in the length of the pendulum affects g by only 0.5 cm. per sec. per sec. while a deviation of 0.0008 sec. in the value of t affects the value of g by 1.6 cm. per sec. per sec. The combined or resultant effect would be $\Delta = \sqrt{\Delta_l^2 + \Delta_t^2} = \sqrt{0.5^2 + 1.6^2} = 1.7$ cm. per sec. per sec. and we might write the final result as $g = 981.5 \pm 1.7$ cm. per sec. per sec. which means that the value of g, as determined, is probably reliable to the nearest 1.7 cm. per sec. per sec. It should be noted in the above computation for Δ_l, Δ_t and Δ that not more than two figures are used in any of the quantities, *i.e.*, $\pi^2 = 9.9$, $t = 1.0$, $l = 100$, etc., the reason being that deviation measures always represent doubtful places. Hence, since more than two doubtful places would be useless, *there is no need of ever keeping more than two figures in each quantity entering into a computation of a deviation measure.*

434. Determination of necessary precision in measured components to secure desired precision in final result. The second or converse problem is as follows: X is to be measured to a certain degree of reliability expressed by $\Delta =$ some definite number. What are the allowable deviations δ_a, δ_b, δ_c . . . in each of the measured components a, b, c . . . such that the combined effect, Δ, of their separate effects, Δ_a, Δ_b, Δ_c . . . shall not exceed the prescribed limit? From the law of errors (Eq. 59) an infinite number of solutions is possible. The *best* solution would be that one which, with the least effort on the part of the investigator, would give the assigned precision. The *easiest* solution and the one that has been found satisfactory, at least as a preliminary adjustment of deviations among the various components, is to assume that each of the components may produce an equal effect on the final result, *i.e.*, to let $\Delta_a = \Delta_b = \Delta_c = \ldots \Delta_n$. From this and Eq. 58 it follows that

$$\Delta_a = \Delta_b = \Delta_c = \ldots \Delta_n = \frac{\Delta}{\sqrt{n}} \tag{60}$$

where n represents the number of measured components. The allowable deviation in any component can then be determined from Eq. 58 and Eq. 60.

Example. It is desired to find the heat developed by an electric heater, within three parts in a thousand (0.3 per cent.), by measuring the current

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used, the voltage at the terminals and the time that the current is flowing. the pressure is about 110 volts, the current about 0.8 amp. and the tim 10 min., how precisely must each component be measured? The formula $H = I.E.t$, where H is in joules, or $H = 0.8 \times 110 \times 600$ joules $= 52{,}800$ joule If H is to be reliable to three parts per thousand, it must then be determin to the nearest 158.4 joules, or keeping two figures only, to the nearest 1 joules. Since there are three components, $n = 3$ and we have

$$\Delta_I = \Delta_E = \Delta_t = \frac{\Delta}{\sqrt{n}} = \frac{160}{\sqrt{3}} = 94 \text{ joules.}$$ Differentiating, we get,

$$\Delta_I = 94 = E_i \delta I \quad \therefore \quad \delta_I = \frac{94}{110 \times 600} = 0.0014 \text{ amp.}$$

$$\Delta_E = 94 = I_i \delta E \quad \therefore \quad \delta_E = \frac{94}{0.8 \times 600} = 0.19 \text{ volts}$$

$$\Delta_t = 94 = IE \delta t \quad \therefore \quad \delta_t = \frac{94}{0.8 \times 110} = 1.1 \text{ sec.}$$

This means that if we assume equal effects and wish to know the heat to th nearest 160 joules, the current must be measured to the nearest 0.0014 amp the voltage to the nearest 0.19 volts and the time to the nearest 1.1 sec. would be very easy to reach this precision in the time measurement if a goo stop watch were used; in fact this interval could be determined to within 0. sec. and therefore the time might be treated as a constant, in which case would be two instead of three and therefore it would not be necessary measure I and E quite so accurately as indicated above.

435. Two classes of formulæ in indirect measurements. The tw **methods shown above** for the direct (Par. 432) and the indirect (Par. 43 methods respectively are perfectly general; consequently by their use an problem may be solved provided all deviation or precision measures are e pressed as actual numerical deviations and not as fractional or percentag deviations. It is found in practice that nearly all formulæ used in indire measurements fall in one or the other of two general groups. Those of th first class include all those functions which contain sums or differences terms, each of which may involve either measured components, or con stants, or both. The general form would be

$$X = Aa^l \pm Bb^m \pm Cc^n \pm \ldots \qquad (61$$

where $A, B, C \ldots$ are constants and $a, b, c \ldots$ are measured quantities entering to the l^{th}, m^{th}, and n^{th} powers respectively. Examples of formulæ o this sort are the expressions for the electromotive force of a standard Clar cell, $E = 1.4340\ [1 - 0.00078\ (t° - 15°)]$, or the resistance of a standard 1 ohm coil, $R = 10[1 + 0.00388\ (t° - 15°)]$.

Those of the second class include all those functions which involv products, quotients or powers of the measured components and constant and do not involve either trigonometric or logarithmetic functions. Th general type would be

$$X = A \cdot a^l \cdot b^m \cdot c^n \ldots \qquad (62$$

where A, n, m, and k are constants (positive, negative, fractional or integral) An example of formulæ of this type is the expression for the modulus of elas ticity for bending, given as $E = Wl^3/4a\,bd^3$, where W is the load at th centre, l is the length between supports, a is the deflection, b the breadth an d the depth of the beam; the formula given above for density (Par. 43 is another example.

436. Percentage method of computing precision. Problems the second class (Par. 435) may be solved much more easily by the fraction or percentage method than by the general method, as will appear from th following. Taking the general form of the function as

$$X = A \cdot a^l \cdot b^m \cdot c^n \ldots \qquad (63$$

and differentiating with respect to each of the variables, and then dividi each of these results by the general formula gives,

$$\frac{\Delta a}{X} = \frac{l \cdot \delta a}{a}, \quad \frac{\Delta b}{X} = \frac{m \cdot \delta b}{b}, \quad \frac{\Delta c}{X} = \frac{n \cdot \delta c}{c}. \qquad (64$$

This shows that a fractional deviation $\delta a/a$ in a produces a fractional devi tion in X which is n times as great, or in per cent. it means that if a is u

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reliable by 1 per cent., X will be unreliable n times 1 per cent. and it is to be noted that the remaining factors in the formula have no effect whatever upon this relation. This enables us to state at once the separate effect of any percentage deviation of a given component and by using the relation

$$\frac{\Delta}{X} = \sqrt{\left(\frac{\Delta_a}{X}\right)^2 + \left(\frac{\Delta_b}{X}\right)^2 + \left(\frac{\Delta_c}{X}\right)^2 + \cdots} \qquad (65)$$

or its equivalent,

$$\frac{\Delta}{X} = \sqrt{\left(l\frac{\delta a}{a}\right)^2 + \left(m\frac{\delta b}{b}\right)^2 + \left(n\frac{\delta c}{c}\right)^2 + \cdots} \qquad (66)$$

we can therefore express the final resultant effect as a percentage deviation.

437. The percentage method is illustrated by the following problem. Measurements for the modulus of elasticity using the above formula are as follows. The weight is 10 kg., reliable to the nearest gram; the length is 1,000 mm., reliable to 0.5 mm.; the deflection is 6.983 mm., reliable to 0.007 mm; the breadth is 4.675 mm., reliable to 0.005 mm.; and the depth is 15.069 mm., reliable to 0.008 mm. The problem is to determine the reliability of the modulus when calculated from the formula $E = W \cdot l^3/4\ a.b.d^3$. The first step is to express all the deviations in per cent. Inspection shows that W is reliable to 0.01 per cent., l to 0.05 per cent., a to 0.10 per cent., b to 0.10 per cent. and d to 0.05 per cent. and by Eq. 71 we get $100\,\Delta w/E = 0.01$ per cent; $100\,\Delta l/E = 0.15$ per cent.; $100\,\Delta a/E = 0.1$ per cent.; $100\,\Delta b/E = 0.10$ per cent.; and $100\,\Delta d/E = 0.15$ per cent. Substituting these values in either Eq. 65 or Eq. 66 we get for the percentage reliability of E: $100\,\Delta/E = \sqrt{0.01^2 + 0.15^2 + 0.10^2 + 0.10^2 + 0.15^2} = 0.25$ per cent., *i.e.*, the combined effect of all the deviations amounts to 0.25 per cent. in the value of the modulus. Then $E = 22{,}420 \pm 56$ kg. per square millimeter.

438. The converse problem in the percentage method would be as follows. It is desired to measure the modulus to 1 per cent.; how precisely must each of the above five components (Par. 437) be measured, and, secondly, can any of them be measured with negligible precision? An inspection of the above measurements, or a knowledge of measurements, would show that the weight might be measured so precisely as to be regarded as a constant, and hence $n = 4$; then we should have, assuming equal effects, $\Delta l/E = \Delta_a/E = \Delta_b/E = \Delta_d/E = \Delta/E\sqrt{4} = 1/100\sqrt{4} = 1/200 = 0.5$ per cent. Applying Eq. 71 we find the percentage deviations to be as follows: $100\,\delta l/l = 0.5/3 = 0.17$ per cent; $100\,\delta_a/a = 0.5$ per cent.; $100\,\delta_b/b = 0.5$ per cent.; $100\,\delta_d/d = 0.5/3 = 0.17$ per cent.

With a little experience one can write the result of either the direct or the converse problem, by the percentage method, from inspection, or at most with a small amount of calculation. It should be noted that the equal-effect method often gives only a first approximation to the best result, for it often is true that one or more components can be measured with negligible precision if equal effects are assumed, in which case a second solution must be made treating such components as constants.

439. Text-books or reference works on precision of measurements.

HOLMAN, S. W.—"Precision of Measurements." John Wiley & Sons, New York, 1894.

GOODWIN, H. M.—"Precision of Measurements and Graphical Methods." McGraw-Hill Book Co., New York, 1913.

PALMER, A. de F.—"The Theory of Measurements." McGraw-Hill Book Co., New York, 1912.

BARTLETT, D. P.—"The Method of Least Squares." Massachusetts Institute of Technology, 1900.

MERRIMAN, M.—"Method of Least Squares." John Wiley & Sons, New York.

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SECTION 4

PROPERTIES OF MATERIALS

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SECTION 4

CONDUCTOR MATERIALS

GENERAL

1. Conductors and non-conductors. All materials possess, in some degree, the property of electric conductivity and the question whether a given material shall be classed as a conductor or a non-conductor is entirely one of degree. Certain materials are readily classified in these two general groups; metals, for instance, are easily classed as conductors, whereas such substances as mica, glass, rubber and mineral oil are classed as non-conductors. Certain other materials are not easily classified, because their properties undergo extreme changes with their degrees of purity, treatment and temperature. In general, all materials which are used commercially for conducting electricity can be classed as conductors; and those materials used commercially for obstructing the flow of electricity can be classed as non-conductors, a better term being *insulators* or *dielectrics*. Substances which are neither good conductors nor good insulators can be termed semi-conductors.

2. Solid conduction, or the property of conduction through bodies in the solid state, is explained in Sec. 2. This type of conduction is the only one considered at length in this section (Sec. 4).

3. Liquid conduction, while it refers mainly to the conduction of **electrolytes** (Sec. 19), also includes liquids of elements in the pure state, as distinguished from chemical solutions, acid or basic. The property of liquid conduction is treated at length in Sec. 19, on "Electrochemistry" (also see Sec. 20, on "Batteries)".

4. Gaseous conduction, or the conducting power of **gases,** usually in a rarefied state, is also outside the scope of Sec. 4 and is taken up in Sec. 19.

5. The theory of conduction is briefly explained in Sec. 2. The electron theory, or modern view of conduction phenomena, is treated more fully in Sec. 22.

6. Effect of temperature. The **resistivity** of most metals becomes greater as the temperature rises. These materials are said to have positive temperature coefficients of resistance. Carbon and electrolytes, on the opposite hand, have negative temperature coefficients; that is, their resistivity becomes less as the temperature rises. The coefficients of alloys are usually variable and change sign at some temperatures. There are certain alloys, such as manganin, which have very small temperature coefficients, but such materials form the exception. It has also been found, in the case of copper, that the temperature coefficient of resistance varies directly as the percentage of conductivity with respect to the annealed copper standard (Par. 41).

7. Temperature coefficient of resistance. The resistance of any conductor, over at least a limited range, can be expressed by the linear equation,

$$R_t = R_0(1 + \alpha_0 t) \qquad \text{(ohms)} \qquad (1)$$

where R_t is the resistance at any temperature t, R_0 is the resistance at 0 deg. cent. and α_0 is the temperature coefficient per deg. from and at zero deg. At some other reference temperature t_1, the resistance is

$$R_t = R_1[1 + \alpha_1(t - t_1)] \qquad \text{(ohms)} \qquad (2)$$

where R_1 is the resistance at t_1 deg. and α_1 is the coefficient from and at the temperature t_1 deg. These formulas take no account of the change of di-

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mensions with change of temperature and therefore apply to the case of conductors of constant mass, usually met in engineering work. For a full discussion of this subject see Dellinger, J. H. "The Temperature Coefficient of Copper," Bulletin of the Bureau of Standards, 1911, Vol. VII, No. 1, p. 71; and "Copper Wire Tables," Circular No. 31, 3rd edition, 1914, Bureau of Standards.

8. **Effect of chemical composition.** The resistivity of most metals is very sensitive to slight changes in chemical composition. Particularly is this true of copper; when alloyed, for example, with 1 per cent. of another metal, its increase in resistivity, measured in per cent., is many times 1 per cent. See Par. **63** and **64**. Therefore it is very essential when stating a value of resistivity for a given substance to state also what the substance is composed of, or if it be so nearly pure that there are no more than small traces of foreign substances, to state its percentage of purity.

9. **Effect of mechanical treatment.** When ductile metals are subjected to cold rolling, drawing, hammering, or to cold working of any kind, they become harder, stronger and slightly more dense. At the same time the resistivity increases, sometimes markedly, and the initial properties can only be approached again by means of the **annealing process**. While this process will sometimes restore the initial properties, at least for most practical purposes, it does not always do so.

WIRE GAGES

10. **The sizes of wire** have been for many years indicated in commercial practice almost entirely by gage numbers, especially in America and England. This practice is accompanied by some confusion because numerous gages are in common use. The most commonly used gage for electrical wires, in America, is the **American wire gage** described fully in Par. **13**. The most commonly used gage for steel wires is the **Steel wire gage** briefly mentioned in Par. **15**.

There is no legal standard wire gage in this country, although a gage for sheets was adopted by Congress in 1893 (see Par. **214**). In England there is a legal standard known as the **Standard wire gage**, mentioned in Par. **17**. In Germany, France, Austria, Italy and other continental countries practically no wire gage is used, but wire sizes are specified directly in millimeters. This system is sometimes called the **Millimeter wire gage** (see Par. **23**). The wire sizes used in France, however, are based to some extent on the old Paris gage ("jauge de Paris de 1857"). For a history of wire gages see Circular No. 31, "Copper Wire Tables," Bureau of Standards, 3rd Edition, Oct. 1, 1914. Also see Circular No. 67, "Wire Gages," 1918.

There is a growing tendency to **abandon gage numbers** entirely and specify wire sizes by the **diameter in mils** (thousandths of an inch). This practice holds particularly in writing specifications, and has the great advantages of being both simple and explicit. A number of the wire manufacturers also encourage this practice, and it was definitely adopted by the United States Navy Dept. in 1911.

11. **The mil** is a term universally employed in this country in connection with wire gages and is a unit of length equal to one thousandth of an inch.

12. **The circular mil** is another universal used term, being a unit of area equal to the area of a circle 1 mil in diameter. Such a circle, however, has an area of 0.7854 (or $\pi/4$) **sq. mil.** Thus a wire 10 mils in diameter has a cross-sectional area of 100 circ. mils or 78.54 sq. mils. Hence, 1 circ. mil equals 0.7854 sq. mil.

13. **The American wire gage**, also known as the **Brown & Sharpe gage**, was devised in 1857 by J. R. Brown. It is usually abbreviated **A. W. G.** This gage has the property, in common with a number of other gages, that its sizes represent approximately the successive steps in the process of wire drawing. Also, like many other gages, its numbers are retrogressive, a larger number denoting a smaller wire, corresponding to the operations of drawing. These gage numbers are not arbitrarily chosen, as in many gages, but follow the mathematical law upon which the gage is founded. The gage numbers and sizes are given in Par. **20**.

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The theoretically exact diameters in this gage, as given in the second column of Par. **30**, contain more significant figures than there is any commercial need for, and hence the large companies have standardised the sizes given in the third column, using the nearest mil for large sizes and the nearest tenth of a mil for the smaller sizes. These commercial sizes were adopted as standard by the United States War Dept. in 1911.

14. The basis of the American wire gage is a simple mathematical law. The gage is formed by the specification of two diameters and the law that a given number of intermediate diameters are formed by geometrical progression. Thus, the diameter of No. 0000 is defined as 0.4600 in. and of No. 36 as 0.0050 in. There are 38 sizes between these two, hence the ratio of any diameter to the diameter of the next greater number is given by the expression

$$\sqrt[39]{\frac{0.4600}{0.0050}} = \sqrt[39]{92} = 1.122\ 932.2$$

The square of this ratio = 1.2610. The sixth power of the ratio, *i.e.*, the ratio of any diameter to the diameter of the sixth greater number = 2.005. The fact that this ratio is so nearly 2 is the basis of numerous useful relations or short cuts in wire computations.

15. The steel wire gage, also known originally as the **Washburn & Moen gage** and later as the **American Steel & Wire Co.'s gage**, was established by Ichabod Washburn about 1830. This gage also, with a number of its sizes rounded off to thousandths of an inch, is known as the **Roebling gage.** It is used exclusively for steel wire. See Par. **30**.

16. The Birmingham wire gage, also known as **Stubs' wire gage** and **Stubs' iron wire gage**, is said to have been established early in the eighteenth century in England, where it was long in use. This gage was used to designate the Stubs' soft wire sizes and should not be confused with Stubs' steel wire gage mentioned in Par. **19**. The numbers of the Birmingham gage were based upon the reductions of size made in practice by drawing wire from rolled rod. Thus, a wire rod was called No. 0, first drawing No. 1, and so on. The gradations of size in this gage are not regular, as will appear from its graph. This gage has been used to a considerable extent for designating iron and steel telegraph wires and the Bell telephone system has standardized No. 8 bare copper. See Par. **30**.

17. The Standard wire gage, which more properly should be designated **(British) Standard wire gage**, is the legal standard of Great Britain for all wires, adopted in 1883. It is also known as the **New British Standard gage**, the **English legal standard gage** and the **Imperial wire gage**. It was constructed by so modifying the Birmingham gage that the difference between consecutive sizes became more regular. While this gage is the one most largely used in England, there is a tendency there, as here, to drop gage numbers and specify sizes by the diameter in mils. This gage has never been extensively used in this country, except by the Bell telephone system which has standardized No. 12 bare copper. See Par. **30**.

18. The Old English wire gage, also known as the **London wire gage** differs very little from the Birmingham gage. It was formerly used to some extent for brass and copper wires, but is now nearly obsolete. See Par. **30**.

19. The Stubs' steel wire gage has a somewhat limited use for tool steel wire and drill rods. It should not be confused with the Birmingham or Stubs' iron wire gage mentioned in Par. **16**. The numbers and sizes are given in Par. **30**. In addition there are twenty-six larger sizes, *Z* to *A*, and thirty smaller sizes, No. 51 to No. 80, besides those given in Par. **30** (see tool catalogue of Brown & Sharpe Mfg. Co., or The L. S. Starrett Co.).

20. The Trenton Iron Co.'s gage, of which the numbers and sizes are given in Par. **30**, is used only to a very limited extent. It differs but slightly from the steel wire gage mentioned in Par. **18**.

21. The French wire gage is an exception to the other gages given in Par. **30** in the respect that its sizes are progressive, instead of retrogressive as the numbers advance. The sizes there given were taken from the American Steel and Wire Co.'s handbook, "Electrical Wires and Cables," 1910.

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21. The Edison standard wire gage was proposed some time before 1867 and was based upon the simple principle that the area of cross-section increased proportionately with the gage numbers. Thus No. 5 = 5,000 circ. mils, No. 10 = 10,000 cir. mils, etc. This gage never came into general use.

23. The Millimeter wire gage, also known as the **Metric wire gage,** is based on giving progressive numbers to the progressive sizes, calling 0.1 mm. diameter No. 1, 0.2 mm. No. 2, etc.

24. The German gage, in which the diameters or thickness are expressed in millimeters, is retrogressive and contains 25 sizes. The gage numbers and sizes are given in Par. **29.**

26. Large sizes of wire, above No. 0000 A.W.G., are specified by the total cross-section in **circular mils.** This applies in particular to large cables.

26. The United States standard sheet gage, for sheet and plate iron and steel, was adopted by Congress on March 3, 1893 (see 27 Stat. L., 746) and established a uniform legal standard for the United States. The numbers and thicknesses in this gage are given in Par. **30,** for comparison with wire gages. A full table of gage numbers, thicknesses and weights is given in Par. **215.**

27. The standard decimal gage for sheet metals, designating the thickness in **mils,** was recommended in 1895 by the Association of American Steel Manufacturers, the American Railway Master Mechanics' Association and the American Society of Mechanical Engineers. There are 38 sizes, ranging from 2 mils to 250 mils. See Par. **216** for a full table of sizes and weights.

28. The measurement of wire diameters may be accomplished in three ways, viz., by means of a micrometer caliper, by means of a wire gage such as that shown in Fig. 1, or by means of a V-gage. The most accurate means is a micrometer caliper, which reads directly to mils, and, by estimating tenths of the smallest scale division, to tenths of a mil. The most accurate type of micrometer is one equipped with a miniature friction clutch, which eliminates errors caused by gripping the wire too firmly between the jaws.



FIG. 1.—Gage for testing the sizes of wires.

29. German wire gage table

Diameters in millimeters

No.	Diam.	No.	Diam.	No.	Diam.	No.	Diam.	No.	Diam.
1	5.50	6	3.75	11	2.50	16	1.375	21	0.750
2	5.00	7	3.50	12	2.25	17	1.250	22	0.625
3	4.50	8	3.25	13	2.00	18	1.125	23	0.562
4	4.25	9	3.00	14	1.75	19	1.000	24	0.500
5	4.00	10	2.75	15	1.50	20	0.875	25	0.438

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30. Tabular comparison of wire gages
Diameters in mils

Gage No.	American Wire Gage (B. & S.) exact sizes	American Wire Gage (B. & S.) commercial sizes	Steel Wire Gage (Wash. & Moen)	Birmingham Wire Gage (Stubs')	(British) Standard Wire Gage	Old English Wire Gage (London)	Stubs' Steel Wire Gage	Trenton Iron Co. Gage	French Gage	U. S. Standard Sheet Gage	Gage No.
7–0	.....	.....	490.0	.....	500.0	.....	.....	.....	.....	500.0	7–0
6–0	.....	.....	461.5	.....	464.0	.....	.....	.....	.....	468.7	6–0
5–0	.....	.....	430.5	.....	432.0	.....	.....	450.0	.....	437.5	5–0
4–0	460.00	460.0	393.8	454.0	400.0	454.0	.....	400.0	.....	406.2	4–0
3–0	409.64	410.0	362.5	425.0	372.0	425.0	.....	360.0	.....	375.0	3–0
2–0	364.80	365.0	331.0	380.0	348.0	380.0	.....	330.0	.....	343.7	2–0
0	324.86	325.0	306.5	340.0	324.0	340.0	.....	305.0	.....	312.5	0
1	289.30	289.0	283.0	300.0	300.0	300.0	227.0	285.0	33.0	281.2	1
2	257.63	258.0	262.5	284.0	276.0	284.0	219.0	265.0	40.0	265.6	2
3	229.42	229.0	243.7	259.0	252.0	259.0	212.0	245.0	50.0	250.0	3
4	204.31	204.0	225.3	238.0	232.0	238.0	207.0	225.0	63.0	234.4	4
5	181.94	182.0	207.0	220.0	212.0	220.0	204.0	205.0	68.0	218.7	5
6	162.02	162.0	192.0	203.0	192.0	203.0	201.0	190.0	83.0	203.5	6
7	144.29	144.0	177.0	180.0	176.0	180.0	199.0	175.0	97.0	187.5	7
8	128.49	128.0	162.0	165.0	160.0	165.0	197.0	160.0	110.0	171.9	8
9	114.42	114.0	148.3	148.0	144.0	148.0	194.0	145.0	120.0	156.2	9
10	101.90	102.0	135.0	134.0	128.0	134.0	191.0	130.0	135.0	140.6	10
11	90.74	91.0	120.5	120.0	116.0	120.0	188.0	117.5	149.0	125.0	11
12	80.81	81.0	105.5	109.0	104.0	109.0	185.0	105.0	162.0	109.4	12
13	71.96	72.0	91.5	95.0	92.0	95.0	182.0	92.5	172.0	93.7	13
14	64.08	64.0	80.0	83.0	80.0	83.0	180.0	80.6	185.0	78.1	14
15	57.07	57.0	72.0	72.0	72.0	72.0	178.0	70.0	197.0	70.3	15
16	50.82	51.0	62.5	65.0	64.0	65.0	175.0	61.0	212.0	62.5	16
17	45.26	45.0	54.0	58.0	56.0	58.0	172.0	52.5	225.0	56.2	17
18	40.30	40.0	47.5	49.0	48.0	49.0	168.0	45.0	238.0	50.0	18
19	35.89	36.0	41.0	42.0	40.0	40.0	164.0	40.0	250.0	43.7	19
20	31.96	32.0	34.8	35.0	36.0	35.0	161.0	35.0	263.0	37.5	20
21	28.46	28.5	31.7	32.0	32.0	31.5	157.0	31.0	279.0	34.4	21
22	25.35	25.3	28.6	28.0	28.0	29.5	155.0	28.0	290.0	31.2	22
23	22.57	22.6	25.8	25.0	24.0	27.0	153.0	25.0	303.0	28.1	23

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80. Tabular comparison of wire gages.—*Continued*

Diameter in mils.

Gage No.	American Wire Gage (B. & S.) exact sizes	American Wire Gage (B. & S.) commercial sizes	Steel Wire Gage (Wash. & Moen)	Birmingham Wire Gage (Stubs')	(British) Standard Wire Gage	Old English Wire Gage (London)	Stubs' Steel Wire Gage	Trenton Iron Co. Gage	French Gage	U.S. Standard Sheet Gage	Gage No.
24	20.10	20.1	23.0	22.0	22.0	25.0	151.0	22.5	316.0	25.0	24
25	17.90	17.9	20.4	20.0	20.0	23.0	148.0	20.0	331.0	21.9	25
26	15.94	15.9	18.1	18.0	18.0	20.5	146.0	18.0	342.0	18.7	26
27	14.20	14.2	17.3	16.0	16.4	18.75	143.0	17.0	356.0	17.2	27
28	12.64	12.6	16.2	14.0	14.8	16.50	139.0	16.0	371.0	15.6	28
29	11.26	11.3	15.0	13.0	13.6	15.50	134.0	15.0	383.0	14.1	29
30	10.03	10.0	14.0	12.0	12.4	13.75	127.0	14.0	394.0	12.5	30
31	8.928	8.9	13.2	10.0	11.6	12.25	120.0	13.0	408.0	10.9	31
32	7.950	8.0	12.8	9.0	10.8	11.25	115.0	12.0	419.0	10.1	32
33	7.080	7.1	11.8	8.0	10.0	10.25	112.0	11.0	431.0	9.4	33
34	6.305	6.3	10.4	7.0	9.2	9.50	110.0	10.0	448.0	8.6	34
35	5.615	5.6	9.5	5.0	8.4	9.00	108.0	9.5	458.0	7.8	35
36	5.000	5.0	9.0	4.0	7.6	7.50	106.0	9.0	472.0	7.0	36
37	4.453	4.5	8.5	.....	6.8	6.50	103.0	8.5	485.0	6.6	37
38	3.965	4.0	8.0	.....	6.0	5.75	101.0	8.0	499.0	6.2	38
39	3.531	3.5	7.5	.....	5.2	5.00	99.0	7.5	509.0	.....	39
40	3.145	3.1	7.0	.....	4.8	4.50	97.0	7.0	524.0	.....	40
41	.....	.....	6.6	.....	4.4	.....	95.0	.....	.....	.....	41
42	.....	.....	6.2	.....	4.0	.....	92.0	.....	.....	.....	42
43	.....	.....	6.0	.....	3.6	.....	88.0	.....	.....	.....	43
44	.....	.....	5.8	.....	3.2	.....	85.0	.....	.....	.....	44
45	.....	.....	5.5	.....	2.8	.....	81.0	.....	.....	.....	45
46	.....	.....	5.2	.....	2.4	.....	79.0	.....	.....	.....	46
47	.....	.....	5.0	.....	2.0	.....	77.0	.....	.....	.....	47
48	.....	.....	4.8	.....	1.6	.....	75.0	.....	.....	.....	48
49	.....	.....	4.6	.....	1.2	.....	72.0	.....	.....	.....	49
50	.....	.....	4.4	.....	1.0	.....	69.0	.....	.....	.....	50

See Bureau of Standards Circular No. 67, "Wire Gages," for a combined table of sizes in the principal wire gages.

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COPPER

31. General properties. Copper, which is by far the most importar metal in the electrical industry, is a highly malleable and ductile metal, of reddish color. The density varies slightly, depending on the physical stat an average value being 8.9. Copper melts at 1,083 deg. cent.* (1,981 de fahr.), and in the molten state has a sea-green color. When heated to a ver high temperature it vaporizes, and burns with a characteristic green flam Copper boils at 2,310 deg. cent. (4,190 deg. fahr.).† Molten copper readil absorbs oxygen, hydrogen, carbon monoxide and sulphur dioxide; on coolin the occluded gases are liberated, tending to give rise to blow holes and porou castings. The presence of lead in molten copper tends to drive off bot carbon dioxide and water vapor.

Copper when exposed to ordinary air becomes oxidized, turning to black color, but the coating is protective and the oxidizing process is nc progressive as with iron and steel. When exposed however to moist a containing carbon dioxide, it becomes coated with green basic carbonat It is also affected by sulphur dioxide. It resists the action of hydrochlori sulphuric and strong nitric acids, at ordinary temperatures, but is acte upon by dilute nitric acid.

The electrical conductivity of copper depends most critically on its degre of chemical purity (see Par. **33**) and also, in much less degree, upon th physical state, being reduced slightly (from 2 per cent. to 4 per cent.) b cold rolling and drawing. The tensile properties depend greatly upon th physical state, being much improved by cold rolling and drawing.

The alloys of copper are exceedingly numerous, both for electrical an mechanical purposes. Among the most important for electrical purpos are German or nickel silver, bronze and brass. Copper solders readily wit ordinary low-temperature solders; solder alloys with copper at about 23 deg. cent. (460 deg. fahr.). Also see Bur. of Standards Circular No. 73, o "Copper."

32. Commercial grades of copper. In the copper trade there ar three recognized grades of copper known as **electrolytic, Lake,** and **cast ing.**‡ The first, electrolytic, is that refined by the electrolytic method an is highly pure (see Par. **34**). The second, Lake, is also highly pure, in it natural or mineral state, and requires simply to be melted down to bar for convenient handling (see Par. **36**). The third kind of copper, known a casting copper, contains more impurities and consequently runs lower i conductivity. It is, as its name implies, more suitable for mechanical tha electrical applications (Par. **38**).

33. Density of copper. The internationally accepted density annealed copper,§ expressed in grams per cu. cm. at 20 deg. cent., **8.89**; this of course is also the specific gravity at 20 deg. cent., referred t water at 4 deg. cent. The American Society for Testing Materials ha accepted this value, on account of its international endorsement, but co siders that a value of 8.90 is probably nearer the exact truth. A density 8.89 at 20 deg. cent. corresponds to 8.90 at 0 deg. cent. In English uni the international standard equals 0.32117 lb. per cu. in. Also see "Copp Wire Tables," circular No. 31, Bureau of Standards, Washington, D. C.; an "Smithsonian Physical Tables," Washington, D. C., 1920, 7th rev. ed., p. 33

34. Electrolytic copper. The electrolytic refinement of copper (see Sec. 19) not only produces metal of the highest purity, but it is ec

* "Tables Annuelles de Constantes Et Données. Numériques, de Chimi de Physique et de Technologie;" University of Chicago Press, 1912; Vo I (1910), p. 48.

† Fulton, C. H. "Principles of Metallurgy;" McGraw-Hill Book Co New York, 9111; p. 74.

‡ See report of Committee B-2, on Non-ferrous Metals and Alloy American Society for Testing Materials, 16th annual meeting, June 24-2 1913.

§ Ratified at the meeting of the International Electrotechnical Commissio held in Berlin, Sept. 1 to 6, 1913; see *Trans.* A. I. E. E., Vol. XXXII, 2148.

‖ Addicks, L. "Electrolytic Copper;" Journal of the Franklin Institut Philadelphia, Pa., Dec., 1905.

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nomically necessary when precious metals are present in the ore. This grade of copper should run higher than 99.88 per cent. of pure metal. An analysis of average electrolytic copper, representing neither the best nor the worst, was furnished by Mr. Lawrence Addicks and appears in Par. 35. The minute quantities of impurities there shown of course fluctuate from time to time in any given refinery, and there are usually certain typical differences among the refineries, owing to individual characteristics of the bullion supply. Wire bars of electrolytic copper are made by melting down the cathode copper in a furnace and casting in the desired form and size.

35. Average analysis of commercial electrolytic copper

(L. Addicks)

Conductivity 100 per cent.			
Element	Per cent.	Element	Per cent.
[illegible]	99.93	Tellurium	0.0006
[illegible]	0.0010	Selenium	0.0003
[illegible]	0.004	Iron	0.0030
[illegible]	0.0008	Aluminum	0.0020
[illegible]	0.0018	Phosphorus	0.0004
[illegible]ony	0.0030	Silver	(1)
[illegible]th	0.0002	Gold	(2)

(1) 4 oz. per ton. (2) 0.005 oz. per ton.
[illegible] see Bur. of Standards Circular No. 73, on "Copper."

36. Lake copper is the grade of material which comes from the northern Michigan (U. S. A.) peninsular, being the only known variety which occurs in nature with the purity of electrolytically refined metal. The rock ore containing the metal is crushed in stamp mills, concentrated and melted, requiring no further treatment than "poling" (introducing sticks of green hardwood into the metal) to reduce the oxides and bring it to tough pitch.

Some of the Lake copper coming from the deeper ore deposits has been found to contain appreciable quantities of arsenic, which is very injurious to electrical conductivity.* Where the quantity of arsenic is high enough to injure the conductivity appreciably, the metal is either sold as arsenical copper or else refined electrolytically.

37. Specifications for electrolytic and Lake Copper wire bars have been adopted by the American Society for Testing Materials. See "A. S. T. M. Standards" for full details.

38. Casting copper is more or less impure copper, too low in conductivity for electrical uses, but entirely suitable for most other applications. There are three sources of this grade of copper: (1) fire-refined copper from virgin sources; (2) copper electrolytically produced by deposition from impure liquors; (3) and copper reclaimed from secondary sources. The copper contents of the better known brands of casting copper run in general over 99 per cent., but some will run less. It is, as its name implies, exclusively a foundry copper.

39. Standards of resistivity. The table in Par. 40 presents a summary of the standards of resistivity, temperature coefficient and resistivity which have been most in use. The particular standard temperature in each column is indicated by enclosure in parentheses ( ), and the other values are computed from the standard temperature. A full discussion of these values will be found in "Copper Wire Tables," Circular No. 31, Bureau of Standards, pp. 5 to 10. The latest accepted value of resistivity is the "**International Annealed Copper Standard,**" given in column 8; all tables given in this section for annealed copper wire are based on this standard, which is covered more specifically in Par. 41.

* Addicks, L. "The Effect of Impurities on the Electrical Conductivity of Copper;" *Trans.* A. I. M. E., 1905.

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40. Table of various values for resistivity, temperature coefficient, and density of annealed copper

Temperature (deg. cent.)	1 England (Eng. Stds. Com., 1904)	2 Germany, Old "Normal Kupfer," density 8.91	3 Germany, Old "Normal Kupfer," assuming density 8.89	4 Lindeck, Matthiessen value, assuming density 8.89	5 A. I. E. E. before 1907 (Matthiessen value)	6 A. I. E. E., 1907 to 1910	7 Bureau of Standards and A. I. E. E., 1911	8 "International Annealed Copper Standard"
				Restivity in Ohms (meter, gram)				
0	0.14136	0.13959	0.13927	0.14157	(**0.14172**)	(**0.14172**)	0.14106	0.14133
15	0.15043	(**0.14850**)	(**0.14816**)	(**0.14997**)	0.15014	0.15065	0.15003	0.15029
(15.6)	(**0.1508**)	.....	.....	.....	.....	.....	.....	.....
20	0.15346	0.15147	0.15113	0.15285	0.15302	0.15363	(**0.15302**)	(**0.15328**)
25	0.15648	0.15444	0.15409	0.15576	0.15593	0.15661	0.15601	0.15626
				Temperature Coefficient				
0	(**0.00428**)	0.00425	0.00425	(*)	(*)	(**0.0042**)	** (0.00427)	** (0.00427)
15	0.00402	(**0.004**)	(**0.004**)	.....	.....	0.00395	** (0.00401)	** (0.00401)
20	0.00394	0.00392	0.00392	.....	.....	0.00387	** (**0.00394**)	** (**0.00393**)
25	0.00386	0.00384	0.00384	.....	.....	0.00380	** (0.00386)	** (0.00385)
				Density				
	† 8.89	8.91	(8.89)	(8.89)	8.89	8.89	†† 8.89	†† 8.89

* Matthiessen's formula: $\lambda_t = \lambda_0 (1 - 0.0038701t + 0.000009009\, t^2)$. λ_t and λ_0 = reciprocal of resistance at t deg. and 0 deg. cent. respectively.

** This temperature coefficient applies only to this particular resistivity. The temperature coefficient is considered to be proportional to conductivity. Expressed otherwise, the change of *resistivity* per deg. cent. is considered to be a constant, viz., 0.000597 ohm (meter, gram).

† At 15.6 deg. cent.

†† This is the density at 20 deg. cent. It corresponds to 8.90 at 0 deg. cent.

NOTE.—Black-faced figures refer to the

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41. **The International Annealed Copper Standard** is the internationally accepted value* for the resistivity of annealed copper of 100 per cent. conductivity. This standard is expressed in terms of mass-resistivity as **0.15328 ohm (meter, gram)**, or the resistance of a uniform round wire 1 m. long weighing 1 gram, at the standard temperature of **20 deg. cent.** Equivalent expressions of the annealed copper standard, in various units of mass resistivity and volume resistivity, are as follows:

0.15328	ohm (meter, gram)	at 20 deg. cent.
875.20	ohms (mile, lb.)	
1.7241	microhm-cm.	
0.67879	microhm-in.	
10.371	ohms (mil, ft.)	
0.017241	ohm (meter, mm.²)	

It may be convenient to note that a value of 0.017241 ohm (meter, mm.²) is exactly $\frac{1}{58}$ ohm, so that the volume conductivity at 20 deg. cent. can be expressed 58 mho (meter, mm.²).

It is important to observe that weight-measure rather than volume-measure is commercially the more important in wire calculations, since wire is sold by the pound. Therefore the most attention should be given to mass-resistivity and mass resistance.

42. **Temperature coefficient of mass resistance.** This coefficient, which applies to resistance calculations when a conductor is defined in terms of its mass, is the one commonly employed in engineering calculations; that is to say, in common practice, the mass of a conductor remains the same at all temperatures, and changes of volume, length, or sag are disregarded. *It is* important to note that it does not apply to a conductor defined in terms of its volume.

The temperature coefficient (for constant mass) of the annealed copper standard, 100 per cent. conductivity, is 0.00393 per deg. cent., at 20 deg. cent. The coefficient changes with the temperature of reference, as given in Par. 40, column 8.

The coefficients for copper of less than standard (or 100 per cent.) **conductivity** is proportional to the actual conductivity, expressed as a decimal percentage. Thus if n is the percentage conductivity (95 per cent. = 0.95), the temperature coefficient will be $\alpha'_t = n\alpha_t$, where α_t is the coefficient of the annealed copper standard.

The coefficients given in the table in Par. 43 were computed from the formula

$$\alpha_t = \frac{1}{\frac{1}{n(0.00393)} + (t_1 - 20)} \qquad (3)$$

The quantity $-T$ given in the last column (Par. 43) is the inferred absolute zero of temperature, assuming a linear relationship between resistance and temperature. At the absolute zero of temperature the resistance would be zero.

43. **Table of temperature coefficients of copper for different initial temperatures (centigrade) and different conductivities**

Ohms (meter, gram) at 20 deg. cent.	Per cent. conductivity	α_0	α_{20}	α_{25}	$-T$, "Inferred absolute zero"
0.16134	95	0.00403	0.00373	0.00367	−247.8
0.15966	96	0.00408	0.00377	0.00370	−245.1
0.15802	97	0.00413	0.00381	0.00374	−242.3
0.15753	97.3	0.00414	0.00382	0.00375	−241.5
0.15640	98	0.00417	0.00385	0.00378	−239.6
0.15482	99	0.00422	0.00389	0.00382	−237.0
(0.15328)	100	0.00427	(0.00393)	0.00385	−234.4
0.15176	101	0.00431	0.00397	0.00389	−231.9

Parentheses indicate the defined standard values.

*Ratified at the meeting of the International Electrotechnical Commission held in Berlin, Sept. 1 to 6, 1913; See *Trans.* A. I. E. E., Vol. XXXII, p. 2156.

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44. Reduction of observations to standard temperature. A tab of convenient corrections and factors for reducing resistivity and resistan to standard temperature, 20 deg. cent., will be found in "Copper Wi Tables," Circular No. 31, Bureau of Standards.

45. Calculation of per cent. conductivity. The per cent. co ductivity of a sample of copper is calculated by dividing the resistiv of the International Annealed Copper Standard at 20 deg. cent. by t resistivity of the sample at 20 deg. cent. Either the mass resistivity volume resistivity may be used. Inasmuch as the temperature coefficie of copper varies with the conductivity, it is to be noted that a differe value will be found if the resistivity at some other temperature is use This difference is of practical moment in some cases. In order that suc differences shall not arise, it is best always to use the 20 deg. cent. value resistivity in computing the per cent. conductivity of copper. When th resistivity of the sample is known at some other temperature, t, it is ver simply reduced to 20 deg. cent. by adding the quantity $(20-t)$ multiplie by the "resistivity-temperature constant," given in Par. 46.

46. Resistivity-temperature constant. The *change of resistivity* pe *degree* may be readily calculated, taking account of the expansion of the met with rise of temperature. The proportional relation between temperatur coefficient and conductivity may be put in the following convenient form fo reducing *resistivity* from one temperature to another: *The change of resistivi of copper per degree cent. is a constant, independent of the temperature of refe ence and of the sample of copper. This "resistivity-temperature constant" ma be taken, for general purposes, as* 0.00060 *ohm (meter, gram), or* 0.006 *microhm-cm.* For further details, see "Copper Wire Tables," Circular No 3 Bureau of Standards, Washington, D. C.

47. Complete copper-wire tables, based on the Internation Annealed Copper Standard, are given in Par. 50, and represent approx mately an average of the present commercial conductivity of copper. Fo annealed wires, the resistivity is independent of the size. These tables a reproduced directly from Circular No. 31, 3rd Edition, issued by the Bures of Standards. The quantities were computed to five significant figures an rounded off to the fourth place, being therefore correct within 1 in the fourt significant figure. The volume resistivity at 20 deg. cent., used in calculatin these tables, was 0.67879 microhm-in. and the density, 8.89 at 20 deg. cen or 0.321,17 lb. per cu. in. The tables in Circular No. 31 contain additiona columns for 0 deg., 15 deg., 25 deg. and 75 deg. cent. What the tables show the resistance at various temperatures, of a wire which at 20 deg. cent. 1,000 ft. long and has the specified diameter, and which varies in length an diameter at other temperatures.

48. Explanatory notes on copper wire tables.

NOTE 1.—The *fundamental resistivity* used in calculating the tables is th International Annealed Copper Standard, viz., 0.15328 ohm (meter, gram at 20 deg. cent. The *temperature coefficient* for this particular resistivi is $\alpha_{20} = 0.00393$, or $\alpha_0 = 0.00427$. However, the temperature coefficient proportional to the conductivity; and hence the change of *resistivity* p deg. cent. is a constant, 0.000597 ohm (meter, gram). The "consta mass", temperature coefficient of any sample is

$$\alpha_t = \frac{0.000597 + 0.000005}{\text{resistivity in ohms (meter, gram) at } t \text{ deg. cent.}}$$

The *density* is 8.89 g. per cu. cm.

NOTE 2.—The values given in the tables are only for annealed copp of the standard resistivity. The user of the table must apply the prop correction for copper of any other resistivity. Hard-drawn copper may taken as about 2.7 per cent. higher resistivity than annealed copper.

NOTE 3.—This table is intended as an ultimate reference table, and computed to a greater precision than is desired in practice. The practic user of a wire table is referred to the "Working Tables," Par. 51.

49. Working copper-wire tables, based on the International A nealed Copper Standard, are given in Par. 51. This table is carried on to three significant figures, and is more convenient for most practical wor The table itself is adapted from Circular No. 31, 3d edition, issued by t Bureau of Standards, and amplified by the addition of values based on t mile unit.

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50. Complete wire table, standard annealed copper
American wire gage (B. & S.). English units

Size (B. & S. gage)	Diameter in mils at 20 deg. cent.	Cross-section at 20 deg. cent.		Ohms per 1,000 ft.*	
		Circular mils	Square inches	20 deg. cent. (= 68 deg. fahr.)	50 deg. cent. (= 122 deg. fahr.)
0000	460.0	211,600.0	0.1662	0.04901	0.05479
000	409.6	167,800.0	0.1318	0.06180	0.06909
00	364.8	133,100.0	0.1045	0.07793	0.08712
0	324.9	105,500.0	0.08289	0.09827	0.1099
1	289.3	83,690.0	0.06573	0.1239	0.1385
2	257.6	66,370.0	0.05213	0.1563	0.1747
3	229.4	52,640.0	0.04134	0.1970	0.2203
4	204.3	41,740.0	0.03278	0.2485	0.2778
5	181.9	33,100.0	0.02600	0.3133	0.3502
6	162.0	26,250.0	0.02062	0.3951	0.4416
7	144.3	20,820.0	0.01635	0.4982	0.5569
8	128.5	16,510.0	0.01297	0.6282	0.7023
9	114.4	13,090.0	0.01028	0.7921	0.8855
10	101.9	10,380.0	0.008155	0.9989	1.117
11	90.74	8,234.0	0.006467	1.260	1.408
12	80.81	6,530.0	0.005129	1.588	1.775
13	71.96	5,178.0	0.004067	2.003	2.239
14	64.08	4,107.0	0.003225	2.525	2.823
15	57.07	3,257.0	0.002558	3.184	3.560
16	50.82	2,583.0	0.002028	4.016	4.489
17	45.26	2,048.0	0.001609	5.064	5.660
18	40.30	1,624.0	0.001276	6.385	7.138
19	35.89	1,288.0	0.001012	8.051	9.001
20	31.96	1,022.0	0.0008023	10.15	11.35
21	28.46	810.1	0.0006363	12.80	14.31
22	25.35	642.4	0.0005046	16.14	18.05
23	22.57	509.5	0.0004002	20.36	22.76
24	20.10	404.0	0.0003173	25.67	28.70
25	17.90	320.4	0.0002517	32.37	36.18
26	15.94	254.1	0.0001996	40.81	45.63
27	14.20	201.5	0.0001583	51.47	57.53
28	12.64	159.8	0.0001255	64.90	72.55
29	11.26	126.7	0.00009953	81.83	91.48
30	10.03	100.5	0.00007894	103.2	115.4
31	8.928	79.70	0.00006260	130.1	145.5
32	7.950	63.21	0.00004964	164.1	183.4
33	7.080	50.13	0.00003937	206.9	231.3
34	6.305	39.75	0.00003122	260.9	291.7
35	5.615	31.52	0.00002476	329.0	367.8
36	5.000	25.00	0.00001964	414.8	463.7
37	4.453	19.83	0.00001557	523.1	584.8
38	3.965	15.72	0.00001235	659.6	737.4
39	3.531	12.47	0.000009793	831.8	929.8
40	3.145	9.888	0.000007766	1,049.0	1,173.0

* Resistance at the stated temperatures of a wire whose length is 1,000 ft. at 20 deg. cent.

50. Complete wire table, standard annealed copper.—*Continued*

Gage No.	Diameter in mils at 20 deg. cent.	Pounds per 1,000 ft.	Feet per pound	Feet per ohm*	
				20 deg. cent. (=68 deg. fahr.)	50 deg. cent. (=122 deg. fahr.)
0000	460.0	640.5	1.561	20,400.0	18,250.0
000	409.6	507.9	1.968	16,180.0	14,470.0
00	364.8	402.8	2.482	12,830.0	11,480.0
0	324.9	319.5	3.130	10,180.0	9,103.0
1	289.3	253.3	3.947	8,070.0	7,219.0
2	257.6	200.9	4.977	6,400.0	5,725.0
3	229.4	159.3	6.276	5,075.0	4,540.0
4	204.3	126.4	7.914	4,025.0	3,600.0
5	181.9	100.2	9.980	3,192.0	2,855.0
6	162.0	79.46	12.58	2,531.0	2,264.0
7	144.3	63.02	15.87	2,007.0	1,796.0
8	128.5	49.98	20.01	1,592.0	1,424.0
9	114.4	39.63	25.23	1,262.0	1,129.0
10	101.9	31.43	31.82	1,001.0	895.6
11	90.74	24.92	40.12	794.0	710.2
12	80.81	19.77	50.59	629.6	563.2
13	71.96	15.68	63.80	499.3	446.7
14	64.08	12.43	80.44	396.0	354.2
15	57.07	9.858	101.4	314.0	280.9
16	50.82	7.818	127.9	249.0	222.8
17	45.26	6.200	161.3	197.5	176.7
18	40.30	4.917	203.4	156.6	140.1
19	35.89	3.899	256.5	124.2	111.1
20	31.96	3.092	323.4	98.50	88.11
21	28.46	2.452	407.8	78.11	69.87
22	25.35	1.945	514.2	61.95	55.41
23	22.57	1.542	648.4	49.13	43.94
24	20.10	1.223	817.7	38.96	34.85
25	17.90	0.9699	1,031.0	30.90	27.64
26	15.94	0.7692	1,300.0	24.50	21.92
27	14.20	0.6100	1,639.0	19.43	17.38
28	12.64	0.4837	2,067.0	15.41	13.78
29	11.26	0.3836	2,607.0	12.22	10.93
30	10.03	0.3042	3,287.0	9.691	8.669
31	8.928	0.2413	4,145.0	7.685	6.875
32	7.950	0.1913	5,227.0	6.095	5.452
33	7.080	0.1517	6,591.0	4.833	4.323
34	6.305	0.1203	8,310.0	3.833	3.429
35	5.615	0.09542	10,480.0	3.040	2.719
36	5.000	0.07568	13,210.0	2.411	2.156
37	4.453	0.06001	16,660.0	1.912	1.710
38	3.965	0.04759	21,010.0	1.516	1.356
39	3.531	0.03774	26,500.0	1.202	1.075
40	3.145	0.02993	33,410.0	0.9534	0.852

* Length at 20 deg cent. of a wire whose resistance is 1 ohm at the state temperatures.

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50. Complete wire table, standard annealed copper.—*Continued*

Gage No.	Diameter in mils at 20 deg. cent.	Ohms per pound		Gage No.	Diameter in mils at 20 deg. cent.	Ohms per pound	
		20 deg. cent. (= 68 deg. fahr.)	50 deg. cent. (= 122 deg. fahr.)			20 deg. cent. (= 68 deg. fahr.)	50 deg. cent. (= 122 deg. fahr.)
0000	460.0	0.00007652	0.00008554	19	35.89	2.065	2.308
000	409.6	0.0001217	0.0001360	20	31.96	3.283	3.670
00	364.8	0.0001935	0.0002163	21	28.46	5.221	5.836
0	324.9	0.0003076	0.0003439	22	25.35	8.301	9.280
1	289.3	0.0004891	0.0005468	23	22.57	13.20	14.76
2	257.6	0.0007778	0.0008695	24	20.10	20.99	23.46
3	229.4	0.001237	0.001383	25	17.90	33.37	37.31
4	204.3	0.001966	0.002198	26	15.94	53.06	59.32
5	181.9	0.003127	0.003495	27	14.20	84.37	94.32
6	162.0	0.004972	0.005558	28	12.64	134.2	150.0
7	144.3	0.007905	0.008838	29	11.26	213.3	238.5
8	128.5	0.01257	0.01405	30	10.03	339.2	379.2
9	114.4	0.01999	0.02234	31	8.928	539.3	602.9
10	101.9	0.03178	0.03553	32	7.950	857.6	958.7
11	90.74	0.05053	0.05649	33	7.080	1,364.0	1,524.0
12	80.81	0.08035	0.08983	34	6.305	2,168.0	2,424.0
13	71.96	0.1278	0.1428	35	5.615	3,448.0	3,854.0
14	64.08	0.2032	0.2271	36	5.000	5,482.0	6,128.0
15	57.07	0.3230	0.3611	37	4.453	8,717.0	9,744.0
16	50.82	0.5136	0.5742	38	3.965	13,860.0	15,490.0
17	45.26	0.8167	0.9130	39	3.531	22,040.0	24,640.0
18	40.30	1.299	1.452	40	3.145	35,040.0	39,170.0

50. Complete wire table, standard annealed copper.—*Continued*

Gage No.	Diameter in mils at 20 deg. cent.	Pounds per ohm		Gage No.	Diameter in mils at 20 deg. cent.	Pounds per ohm	
		20 deg. cent. (= 68 deg. fahr.)	50 deg. cent. (= 122 deg. fahr.)			20 deg. cent. (= 68 deg. fahr.)	50 deg. cent. (= 122 deg. fahr.)
0000	460.0	13,070.0	11,690.0	19	35.89	0.4843	0.4332
000	409.6	8,219.0	7,352.0	20	31.96	0.3046	0.2725
00	364.8	5,169.0	4,624.0	21	28.46	0.1915	0.1713
0	324.9	3,251.0	2,908.0	22	25.35	0.1205	0.1078
1	289.3	2,044.0	1,829.0	23	22.57	0.07576	0.06777
2	257.6	1,286.0	1,150.0	24	20.10	0.04765	0.04262
3	229.4	808.6	723.3	25	17.90	0.02997	0.02680
4	204.3	508.5	454.9	26	15.94	0.01885	0.01686
5	181.9	319.8	286.1	27	14.20	0.01185	0.01060
6	162.0	201.1	179.9	28	12.64	0.007454	0.006668
7	144.3	126.5	113.2	29	11.26	0.004688	0.004193
8	128.5	79.55	71.16	30	10.03	0.002948	0.002637
9	114.4	50.03	44.75	31	8.928	0.001854	0.001659
10	101.9	31.47	28.15	32	7.950	0.001166	0.001043
11	90.74	19.79	17.70	33	7.080	0.0007333	0.0006560
12	80.81	12.45	11.13	34	6.305	0.0004612	0.0004126
13	71.96	7.827	7.001	35	5.615	0.0002901	0.0002595
14	64.08	4.922	4.403	36	5.000	0.0001824	0.0001632
15	57.07	3.096	2.769	37	4.453	0.0001147	0.0001026
16	50.82	1.947	1.742	38	3.965	0.00007215	0.00006454
17	45.26	1.224	1.095	39	3.531	0.00004538	0.00004059
18	40.30	0.7700	0.6888	40	3.145	0.00002854	0.00002553

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51. Working table, standard annealed copper wire American Wire Gage (B. & S.)

Gage No.	Diameter in mils	Cross-section		Ohms per 1,000 ft.		Ohms per mile		Pounds per 1,000 ft.	Pounds per mile
		Circular mils	Square inches	25 deg. cent. (=77 deg. fahr.)	65 deg. cent. (=149 deg. fahr.)	25 deg. cent. (=77 deg. fahr.)	65 deg. cent. (=149 deg. fahr.)		
0000	460.	212,000.	0.166	0.0500	0.0577	0.264	0.305	641.	3380.
000	410.	168,000.	0.132	0.0630	0.0727	0.333	0.384	508.	2680.
00	365.	133,000.	0.105	0.0795	0.0917	0.420	0.484	403.	2130.
0	325.	106,000.	0.0829	0.100	0.116	0.528	0.613	319.	1680.
1	289.	83,700.	0.0657	0.126	0.146	0.665	0.771	253.	1340.
2	258.	66,400.	0.0521	0.159	0.184	0.840	0.972	201.	1060.
3	229.	52,600.	0.0413	0.201	0.232	1.06	1.23	159.	840.
4	204.	41,700.	0.0328	0.253	0.292	1.34	1.54	126.	665.
5	182.	33,100.	0.0260	0.319	0.369	1.68	1.95	100.	528.
6	162.	26,300.	0.0206	0.403	0.465	2.13	2.46	79.5	420.
7	144.	20,800.	0.0164	0.508	0.586	2.68	3.09	63.0	333.
8	128.	16,500.	0.0130	0.641	0.739	3.38	3.90	50.0	264.
9	114.	13,100.	0.0103	0.808	0.932	4.27	4.92	39.6	209.
10	102.	10,400.	0.00815	1.02	1.18	5.39	6.23	31.4	166.
11	91.	8,230.	0.00647	1.28	1.48	6.76	7.81	24.9	132.
12	81.	6,530.	0.00513	1.62	1.87	8.55	9.87	19.8	105.
13	72.	5,180.	0.00407	2.04	2.36	10.8	12.5	15.7	82.9
14	64.	4,110.	0.00323	2.58	2.97	13.6	15.7	12.4	65.5
15	57.	3,260.	0.00256	3.25	3.75	17.2	19.8	9.86	52.1
16	51.	2,580.	0.00203	4.09	4.73	21.6	25.0	7.82	41.3
17	45.	2,050.	0.00161	5.16	5.96	27.2	31.5	6.20	32.7
18	40.	1,620.	0.00128	6.51	7.51	34.4	39.7	4.92	26.0
19	36.	1,290.	0.00101	8.21	9.48	43.4	50.1	3.90	20.6
20	32.	1,020.	0.000802	10.4	11.9	54.9	62.8	3.09	16.3

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51. Working table, standard annealed copper wire.—*Continued*

Gage No.	Diameter in mils	Cross-section		Ohms per 1,000 ft.		Ohms per mile		Pounds per 1,000 ft.	Pounds per mile
		Circular mils	Square inches	25 deg. cent. (=77 deg. fahr.)	65 deg. cent. (=149 deg. fahr.)	25 deg. cent. (=77 deg. fahr.)	65 deg. cent. (=149 deg. fahr.)		
21	28.5	810.	0.000636	13.1	15.1	69.2	79.7	2.45	12.9
22	25.3	642.	0.000505	16.5	19.0	87.1	100.	1.94	10.24
23	22.6	509.	0.000400	20.8	24.0	110.	127.	1.54	8.13
24	20.1	404.	0.000317	26.2	30.2	138.	159.	1.22	6.44
25	17.9	320.	0.000252	33.0	38.1	174.	201.	0.970	5.12
26	15.9	254.	0.000200	41.6	48.0	220.	253.	0.769	4.06
27	14.2	202.	0.000158	52.5	60.6	277.	320.	0.610	3.22
28	12.6	160.	0.000126	66.2	76.4	350.	403.	0.484	2.56
29	11.3	127.	0.0000995	83.4	96.3	440.	509.	0.384	2.03
30	10.0	101.	0.0000789	105.	121.	554.	639.	0.304	1.61
31	8.9	79.7	0.0000626	133.	153.	702.	808.	0.241	1.27
32	8.0	63.2	0.0000496	167.	193.	882.	1020.	0.191	1.01
33	7.1	50.1	0.0000394	211.	243.	1110.	1280.	0.152	0.803
34	6.3	39.8	0.0000312	266.	307.	1400.	1620.	0.120	0.634
35	5.6	31.5	0.0000248	335.	387.	1770.	2040.	0.0954	0.504
36	5.0	25.0	0.0000196	423.	488.	2230.	2580.	0.0757	0.400
37	4.5	19.8	0.0000156	533.	616.	2810.	3250.	0.0600	0.317
38	4.0	15.7	0.0000123	673.	776.	3550.	4100.	0.0476	0.251
39	3.5	12.5	0.0000098	848.	979.	4480.	5170.	0.0377	0.199
40	3.1	9.9	0.0000078	1,070.	1,230.	5650.	6490.	0.0299	0.158

This table is correct to three significant figures, only.

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52. Reference to copper-wire tables in other gages. For copper-wire tables in the British Standard Wire Gage and in the Millimeter Gage, based on the International Annealed Copper Standard, see Bulletin No. 31, 3d edition (Oct. 1, 1914), issued by the Bureau of Standards.

53. Conductivity of hard-drawn copper. The conductivity of hard-drawn copper, expressed as a percentage of the conductivity of the annealed copper standard, varies with the size of wire, becoming smaller as the wire becomes smaller. It is impracticable, however, to state any general rule, because of differences in manufacturing practice, as to the number of drawings between annealings, amount of reduction to each drawing, etc. The Bureau of Standards found that the conductivity of No. 12, A.W.G. hard-drawn copper was 97.3 per cent. The copper-wire specifications of the American Society for Testing Materials, call for resistivities which correspond to the following percentage conductivities, based on the annealed copper standard.

	Per cent., conductivity
Annealed copper	98.2
Medium-hard drawn, above 0.325 in.	97.7
Medium-hard drawn, below 0.325 in.	96.7
Hard-drawn, above 0.325 in.	97.2
Hard-drawn, below 0.325 in.	96.2

The density of all these grades of wire is taken as the same, or 8.89 at 20 deg. cent.

54. Temperature coefficient of expansion. The temperature coefficient of linear expansion of copper is approximately 0.000017 per deg. cent. The values given in the "Tables Annuelles de Constantes et Donnés Numériques," for 1910, are as follows (p. 44 and p. 45): Between −190 deg. and 17 deg. cent., 0.00001418; between 17 deg. and 100 deg. cent., 0.00001636; and by Stéphan's determinations (1910),

$$l_t = l_0[1+0.00001607t+0.00000000403t^2] \qquad (5)$$

Matthiessen's mean coefficient* between 0 deg. and 100 deg. cent., was 0.000001666 and Fizeau found the value* at 40 deg. cent. to be 0.00001678. By computation from Stéphan's results the mean coefficient between 0 deg. and 100 deg. cent. is 0.0000165. The mean of these four results is 0.0000166 per deg. cent. The corresponding value in the fahrenheit scale is 0.00000922 per deg.

55. Concentric strand, or cable, is a conductor made up of a straight central wire (or group of wires) surrounded by helical layers of bare wires (or groups of wires), the alternate layers having a twist in opposite directions. The term "concentric-lay" applies when the strands are composed of single bare wires; the term "rope-lay" applies when the strands are made up of groups of wires, each group in concentric lay. All the individual strands are of the same size. If there are n layers over the core of a concentric-lay cable, not counting the core as a layer, the **total number of strands** or wires will be

$$N = 3n(n+1)+1 \qquad (6)$$

The diameter of such a cable is the diameter of the circumscribing circle, or

$$D = d(2n+1) \qquad (7)$$

where d is the diameter of any strand or individual wire. In a rope-lay cable, such as some forms of extra flexible cable, where instead of individual single wires there are groups of wires, each group consisting of a concentric-lay cable, the total number of wires N in the entire cable will be that given by Eq. 6 for concentric-lay cable multiplied by the number of wires in each component group. Thus a rope-lay cable comprising 1 layer, with 7 wires in each group, would have $7\times7=49$ wires, and is sometimes called a 7×7 rope. Such an expression as a 19×7 rope strand means 19 strands, each composed of 7 wires. A 7×7 rope strand is not economical for large conductors and is usually confined to sizes like No. 4 A.W.G. or smaller. For large sizes a 19×7 or 37×7 rope strand is more compact and presents a smoother exterior.

* "Smithsonian Physical Tables;" Washington, D. C., 1920; 7th rev. ed., p. 218.

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The number of circular mils in a cable composed of N wires is

$$C.M. = Nd^2 \tag{8}$$

where d is the diameter of each wire in mils (thousandths of an inch).

The equivalent solid conductor is one having the same number of circular mils, or its diameter is

$$D' = \sqrt{Nd^2} \tag{9}$$

It is *not* equal to the normal cross-section of the cable, because in the last case the strands are cut at a slight angle (due to their pitch) and such a section is therefore larger than the true section, equal to the sum of the normal sections of all the strands, each taken normal to its own axis.

The ratio of the diameter of concentric strand to the diameter of equivalent solid conductor is given by

$$\frac{D}{D'} = \frac{2n+1}{\sqrt{N}} = \sqrt{\frac{4n^2+4n+1}{3n^2+3n+1}} \tag{10}$$

Substitution in this formula from $n = 0$ to $n = 8$, gives the following values of the ratio.

n	N	$\frac{D}{D'}$	n	N	$\frac{D}{D'}$	n	N	$\frac{D}{D'}$
0	1	1.000	3	37	1.151	6	127	1.154
1	7	1.134	4	61	1.152	7	169	1.154
2	19	1.147	5	91	1.153	8	217	1.154

This shows that the larger the number of strands, for a given cross-section the larger will be the outside diameter, approaching, however, a limiting ratio of 1.154. Therefore the size and the cost of a conductor of given cross-section increase as the number of strands increases.

The individual wires of a cable can seldom be drawn to any of the standard gage numbers, because the diameter of the wire is fixed by the required size of the cable, and the number of wires composing it. Also see "Wire In Electrical Construction," John A. Roebling's Sons Co., 1917; and "Electrical Wires and Cables," Amer. Steel & Wire Co., 1910.

56. Standard stranding of concentric lay cables

(Standards of the A. I. E. E.)

Size	Number of wires		Size	Number of wires	
	(*A*)	(*B*)		(*A*)	(*B*)
2.0 cir. in....	91	127	0.4 cir. in.....	19	37
1.5 cir. in....	61	91	No. 4/0.....	19 or 7	19
1.0 cir. in....	61	61	No. 2/0.....	7	19
0.6 cir. in....	37	61	No. 2.....	7	7
0.5 cir. in....	37	37	No. 7 or smaller.	.....	7

Column (*A*) applies to bare, insulated or weather-proof cables for aerial use; column (*B*) applies to insulated cables for other than aerial use. For intermediate sizes, the stranding for the next larger size is used. Conductors of No. 4/0 A. W. G. and smaller are stranded only for certain kinds of applications, or where desired for special reasons. No. 4/0 A. W. G. cable under class (*A*) are usually made of seven strands when bare and 19 strands when insulated or weather proof. Also see Sec. 24, Par. **9400** to **9402** and specifications of A. S. T. M.

57. Pitch or lay of concentric strand. The axial length of one complete turn of any individual strand in a concentric-lay cable, divided by the diameter of the cable, is called the pitch or lay. The **pitch angle** of the cable is shown in Fig. where ac represents the axis of the cable and l is the axial length of one complete twist; b is the length of any individual strand, $l + \Delta l$ in one complete twist; and the angle bac, or θ is the pitch angle. The side bc is equal to the circumference of the circle circumscribing the cable. In this case the pitch p is given by $p = l/d$. There is no fixed

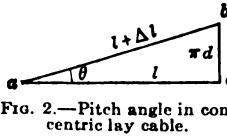


FIG. 2.—Pitch angle in concentric lay cable.

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standard pitch used by all cable manufacturers. Also see "Electrical Wires and Cables," Amer. Steel & Wire Co., 1910, pp. 27 to 35; and Sec. 24, Par. 9034.

58. Increase in mass and resistance due to stranding. The Bureau of Standards has shown in Circular 31 (3rd Edition, 1914, p. 71) that the per cent. increase of resistance of a cable with all the wires perfectly insulated from one another, over the resistance of the "equivalent solid rod," is exactly equal to the per cent. decrease of resistance of a cable in which each wire makes perfect contact with a neighboring wire at all points of its surface. That is, if R_s is the resistance of the equivalent solid rod or wire, R_1 is the resistance of the cable with perfectly insulated wires and R_2 is the resistance of the cable in which all the wires make perfect contact with their neighbors, then $R_s = \frac{1}{2}(R_1 + R_2)$. In general, $R_1 > R_s > R_2$. The resistance of a cable is generally somewhat less than R_1, which is shown by the fact that the actual resistance of a cable increases slightly with age, probably due to the formation of oxide on the contact surfaces.

59. Copper cable tables. The table in Par. 62 gives the properties of bare concentric-lay copper cables, based on the **International annealed copper standard** (see Par. 41). The column headed "Diameter of Wires" was calculated in each case from the total cross-section. The values given for "ohms per 1,000 ft." and "lb. per 1,000 ft." are 2 *per cent. greater* than for a solid rod of cross-section equal to the total cross-section of the wires of the cable. This increment of 2 per cent. means that the values are correct for cables having a pitch of 15.7. If the pitch is different, the resistance and the mass may be calculated by multiplying the values in the table by the factor

$$1 + \left(\frac{493}{p^2} - 2\right)10^{-2} \qquad (11)$$

For example, if the pitch is 12, the resistance and the mass given in the table should be increased 1.4 per cent.; if the pitch is 30, the values should be decreased 1.5 per cent. Also see Sec. 24, Par. 9403.

60. Hemp-centre cables. If the core of a concentric strand is replaced by hemp, the characteristics of the cable are altered in several respects. The diameter of the cable, for a given cross-section, is greater than the diameter of an all-metal cable; the flexibility is slightly greater, for the same size, being more marked in the case of 7 wires than a greater number; and the skin effect, for equal sizes, is slightly diminished. The tensile strength of a hemp-centre cable would be computed on the basis of the cross-section of metal, disregarding the hemp. Such cables are not in general manufactured in standard sizes, but made up to order. See article by D. B. Rushmore in *General Electric Review*, June, 1912, discussing objections to cables of this type.

61. Weight of hemp-centre, concentric-lay, copper cable*

Made of six wires around a hemp centre
(The American Brass Co.)

Size of cable, A.W.G.	Made of	Size of each wire (in.)	Outside diameter (in.)	Approximate weight (lb).	
				Per 1,000 ft.	Per mile
No. 0000	6 wires	0.1879	0.564	673	3,553
No. 000	6 "	0.1672	0.502	551	2,909
No. 00	6 "	0.1489	0.447	418	2,207
No. 0	6 "	0.1326	0.398	332	1,753
No. 1	6 "	0.1181	0.354	266	1,404
No. 2	6 "	0.1052	0.316	212	1,119
No. 3	6 "	0.0937	0.281	167	882
No. 4	6 "	0.0835	0.250	133	702

*The weights for hemp-centre cable were not calculated, but were obtained by weighing lots of finished cable.

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62. Bare concentric-lay cables of standard annealed copper
English Units

Size of cable		Ohms per 1,000 ft.		Pounds per 1,000 ft.	Standard concentric stranding			Flexible concentric stranding		
Circular mils	A.W.G. No.	25 deg. cent. (=77 deg. fahr.)	65 deg. cent. (=149 deg. fahr.)		Number of wires	Diameter of wires, in mils	Outside diameter, in mils	Number of wires	Diameter of wires, in mils	Outside diameter, in mils
2,000,000	.....	0.00539	0.00622	6,180.	127	125.5	1,631.	169	108.8	1,632.
1,900,000	.....	0.00568	0.00655	5,870.	127	122.3	1,590.	169	106.0	1,590.
1,800,000	.....	0.00599	0.00692	5,560.	127	119.1	1,548.	169	103.2	1,548.
1,700,000	.....	0.00634	0.00732	5,250.	127	115.7	1,504.	169	100.3	1,504.
1,600,000	.....	0.00674	0.00778	4,940.	127	112.2	1,459.	169	97.3	1,460.
1,500,000	.....	0.00719	0.00830	4,630.	91	128.4	1,412.	127	108.7	1,413.
1,400,000	.....	0.00770	0.00889	4,320.	91	124.0	1,364.	127	105.0	1,365.
1,300,000	.....	0.00830	0.00958	4,010.	91	119.5	1,315.	127	101.2	1,315.
1,200,000	.....	0.00899	0.0104	3,710.	91	114.8	1,263.	127	97.2	1,264.
1,100,000	.....	0.00981	0.0114	3,400.	91	109.9	1,209.	127	93.1	1,210.
1,000,000	.....	0.0108	0.0124	3,090.	61	128.0	1,152.	91	104.8	1,153.
950,000	.....	0.0114	0.0131	2,930.	61	124.8	1,123.	91	102.2	1,124.
900,000	.....	0.0120	0.0138	2,780.	61	121.5	1,093.	91	99.4	1,094.
850,000	.....	0.0127	0.0146	2,620.	61	118.0	1,062.	91	96.6	1,063.
800,000	.....	0.0135	0.0156	2,470.	61	114.5	1,031.	91	93.8	1,031.
750,000	.....	0.0144	0.0166	2,320.	61	110.9	998.	91	90.8	999.
700,000	.....	0.0154	0.0178	2,160.	61	107.1	964.	91	87.7	965.
650,000	.....	0.0166	0.0192	2,010.	61	103.2	929.	91	84.5	930.
600,000	.....	0.0180	0.0207	1,850.	61	99.2	893.	91	81.2	893.
550,000	.....	0.0196	0.0226	1,700.	61	95.0	855.	91	77.7	855.

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62. Bare concentric-lay cables of standard annealed copper.—*Continued*

Size of cable		Ohms per 1,000 ft.		Pounds per 1,000 ft.	Standard concentric stranding			Flexible concentric stranding		
Circular mils	A.W.G. No.	25 deg. cent. (=77 deg. fahr.)	65 deg. cent. (=149 deg. fahr.)		Number of wires	Diameter of wires, in mils	Outside diameter, in mils	Number of wires	Diameter of wires in mils	Outside diameter, in mils
500,000		0.0216	0.0249	1,540.	37	116.2	814.	61	90.5	815.
450,000		0.0240	0.0277	1,390.	37	110.3	772.	61	85.9	773.
400,000		0.0270	0.0311	1,240.	37	104.0	728.	61	81.0	729.
350,000		0.0308	0.0356	1,080.	37	97.3	681.	61	75.7	682.
300,000		0.0360	0.0415	926.	37	90.0	630.	61	70.1	631.
250,000		0.0431	0.0498	772.	37	82.2	575.	61	64.0	576.
212,000	0000	0.0509	0.0587	653.	19	105.5	528.	37	75.6	533.
168,000	000	0.0642	0.0741	518.	19	94.0	470.	37	67.3	471.
133,000	00	0.0811	0.0936	411.	19	83.7	418.	37	60.0	420.
106,000	0	0.102	0.117	326.	19	74.5	373.	37	53.4	374.
83,700	1	0.129	0.149	258.	19	66.4	332.	37	47.6	333.
66,400	2	0.162	0.187	205.	7	97.4	292.	19	59.1	296.
52,600	3	0.205	0.237	163.	7	86.7	260.	19	52.6	263.
41,700	4	0.259	0.299	129.	7	77.2	232.	19	46.9	234.
33,100	5	0.326	0.376	102.	7	68.8	206.	19	41.7	209.
26,300	6	0.410	0.473	81.	7	61.2	184.	19	37.2	186.
20,800	7	0.519	0.599	64.3	7	54.5	164.	19	33.1	166.
16,500	8	0.654	0.755	51.	7	48.6	146.	19	29.5	147.

NOTE.—This table is based on 2 per cent. increase in mass and resistance over equivalent solid rod, corresponding theoretically to a pitch of 15.7 (see Par. 57 and 59); from Circular No. 31, Third Edition, Oct. 1, 1914, U. S. Bureau of Standards.

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63. Effect of impurities on the conductivity of copper. It is well known that the conductivity of copper is highly sensitive to slight impurities.* A series of progressive tests on the effect of the presence of very small quantities of foreign elements, with respect to electrical conductivity, was made by Mr. Lawrence Addicks. In order to obtain a comparative figure, Mr. Addicks divided the percentage decrease of conductivity by the percentage of impurity added, and obtained the results given in Par. **64**, which are strictly true only for an infinitely small lowering of conductivity. The factor is seen to bear a general relation to the periodic arrangement, becoming smaller with increasing atomic weight within any one group, though there is no evident relation between one group and another. This factor is of use when examining the analysis of a copper which shows low conductivity, as a means of indicating the probable cause of the trouble. Commercial copper when examined under a microscope reveals a structure made up of grains of pure copper enclosed in matrices of impurities, thus forming a complicated chain of two substances. By adding certain impurities the conductivity of the impure portion of the chain may be increased without changing that of the copper itself, thus showing an increase in the total conductivity of the chain.

64. Relation between percentage impurity and percentage change in conductivity

(Lawrence Addicks, *Proc.* A. I. M. E., Vol. XXXVI, p. 18, 1906)

Periodic group	Element	Factor*	Atomic weight	Periodic group	Element	Factor*	Atomic weight
I	Silver.....	6	108	V	Phosphorus**	3000	31
I	Gold.....	10	197	V	Arsenic.....	720	75
II	Zinc.....	30	65	V	Antimony....	190	120
II	Cadmium..	9	112	V	Bismuth.....	4	200
III	Aluminium	500	27	VI	Oxygen.....	25	16
IV	Silicon.....	70	28	VI	Sulphur.....	8	32
IV	Tin.....	67	119	VI	Tellurium....	4	128
IV	Lead.....	3	207	VII	Iron.....	140	56

$$* \text{ Factor} = \frac{\text{Percentage decrease of conductivity}}{\text{Percentage of impurity added}}.$$

** This value is probably too high and later results indicate an average value of about 600.

65. Tensile strength. The mechanical properties of copper exten over a considerable range, depending on its state of hardness. The tensil strength of **annealed copper wire** ranges from about 32,000 lb. or 34,00 lb. per sq. in., in the larger sizes, to as high as 40,000 lb. per sq. in. in th smaller sizes; a very fair assumption is 34,000 lb. as a representative value.

The process of cold drawing increases the strength quite rapidly. S called **medium hard**, or half hard, copper wire has a tensile strength in t larger sizes ranging from 40,000 lb. to 50,000 lb. per sq. in., and in the small sizes from 50,000 lb. to 60,000 lb. per sq. in.

Hard-drawn wire has a tensile strength ranging from 50,000 lb. per s in. in the large sizes to about 65,000 lb. per sq. in. in the small sizes, or 68,0 lb. in the very small sizes.

Fig. 3 shows the results obtained by Addicks† in making a determinati

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* Perrine, F. A. C. "Conductors for Electrical Distribution;" D. V Nostrand Co., New York, 1903, pp. 8 to 10.

Addicks, L. "The Electrical Conductivity of Commercial Copper;" *Tra* A. I. E. E., Vol. XXII, p. 695 (1903).

Addicks, L. "The Effect of Impurities on the Electrical Conductivity Copper;" *Trans.* A. I. M. E., Vol. XXXVI, 1906, p. 18.

Hoffman, H. O. "Metallurgy of Copper;" McGraw-Hill Book Co., N York, 1914.

† Addicks, L. "The Electrical Conductivity of Commercial Copper *Trans.* A. I. E. E., Vol. XXII (1903), p. 695.

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of the relationship between tensile strength and conductivity of copper wire. This shows, among other things, that the properties of copper, after it has been through a cycle of hard drawing and annealing, are not completely restored, but nearly so.

Concentric strand or cable should have a total strength equal at least to 90 per cent. of the strength of its component strands. The ultimate strength, however, is theoretically a function of the pitch, and in addition the internal stresses in a cable under load are very complex, so that a factor of 90 per cent. is approximate.

Cast copper ranges in tensile strength from 20,000 lb. to 30,000 lb. per sq. in. and has a crushing strength of about 40,000 lb. per sq. in.

The tinning process, applied to copper wires which are intended to receive any kind of insulation containing rubber as an ingredient, removes some of the temper of hard-drawn wire and hence impairs its tensile strength. Also see tables of tensile strength in A.S.T.M. specifications for copper wire, current issue of "Year Book."

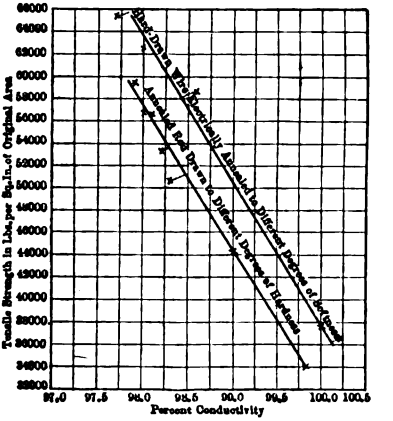


FIG. 3.—Relationship between conductivity and tensile strength in copper wire (Addicks).

66. Elongation and fracture. Annealed copper is very ductile and has an ultimate elongation of 35 per cent. to 40 per cent. in the large sizes of wire; in the smaller sizes the elongation decreases to a value of 20 per cent. to 25 per cent. The elongation of medium hard and of hard-drawn wire ranges from 4 per cent. in the largest size to about 1 per cent. in the smallest. The fracture of cast copper is granular and irregular, while that of forged, rolled, or drawn copper is fibrous, with a silky luster. At fracture there is considerable reduction of area, with drawn copper, in the plane of rupture.

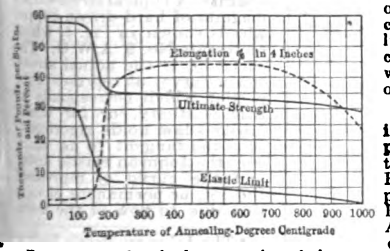


FIG. 4.—Mechanical properties of electrolyte copper as affected by temperature (Hoffman).

67. The effect of annealing temperature on tensile properties of copper is illustrated in Fig. 4. See Hoffman, H. O. "Metallurgy of Copper;" New York, McGraw-Hill Book Co., Inc., 1914, page 5. Also see Bur. of Standards Circular No. 73, "Copper," p. 50.

68. Effect of impurities on tensile strength. One of the most common impurities in copper is oxygen, in the form of suboxid of copper (Cu_2O). While minute quantities are not harmful, an excess is the cause of brittleness. The presence of lead makes the metal "red short" or "hot short." The presence of bismuth or tellurium makes the metal both "red short" and "cold short."

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69. Table of breaking loads of copper wire
(Based on tensile requirements of the American Society for Testing Materials)

Gage No. A.W.G.	Diam. in mils	Breaking load (lb.)		
		Annealed	Medium hard	Hard drawn
0000	460	5,980	6,980 –8,140	8,140
000	410	4,750	5,680 –6,600	6,730
00	365	3,780	4,620 –5,360	5,540
0	325	2,980	3,730 –4,310	4,520
1	289	2,370	3,020 –3,480	3,680
2	258	1,930	2,450 –2,810	3,000
3	229	1,530	1,980 –2,270	2,440
4	204	1,210	1,590 –1,820	1,970
5	182	963	1,260 –1,450	1,590
6	162	763	1,010 –1,150	1,280
7	144	607	810 – 925	1,030
8	128	481	646 – 737	828
9	114	381	515 – 587	663
10	102	314	410 – 467	528
11	91	249	328 – 373	423
12	81	198	262 – 298	337
13	72	157	209 – 237	268
14	64	124	167 – 189	214
15	57	98.6	131 – 151	170
16	51	78.2	106 – 120	135
17	45	62.0	84.8– 96.1	108
18	40	49.3	67.9– 76.8	85.8
(English gages)				
8 B.W.G.	165	792	1,050 –1,200	1,330
10 B.W.G.	134	522	698 – 797	894
12 S.W.G.	104	314	427 – 487	551
13 S.W.G.	92	256	337 – 383	435
14 S.W.G.	80	194	256 – 292	330
16 B.W.G.	65	128	171 – 195	220

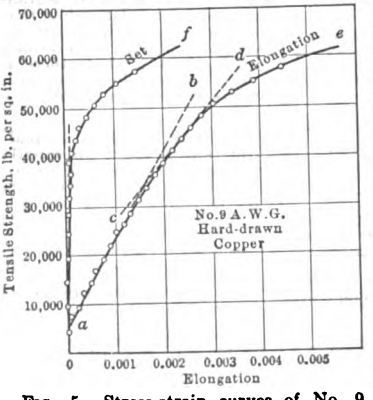


FIG. 5.—Stress-strain curves of No. 9 A.W.G. hard-drawn copper wire (Watertown Arsenal test).

70. Stress-strain dia
grams. A typical stress-stra
diagram of hard-drawn copp
wire is shown in Fig. 5, whi
represents No. 9 A.W.G. T
curve *ae* is the actual stre
strain curve; *ab* represents t
portion which corresponds
true elasticity, or for whi
Hooke's law holds rigorous
cd is the tangent to *ae* whi
fixes the Johnson elastic lim
and the curve *af* represe
the set, or permanent elon
tion due to flow of the me

* The Johnson elastic limi
that point on the stress-str
curve at which the natural t
gent is equal to 1.5 times
tangent of the angle of
straight or linear portion of
curve, with respect to the
of ordinates, or Y axis.

Johnson, J. B., "Materials
Construction," John Wiley
Sons, New York, 1912.

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under stress, being the difference between *ab* and *ac*. The test length was 20 in. and the elongation at rupture was 1.3 per cent. The true elastic limit was 27,000 lb. per sq. in. or 44 per cent. (rather low, below average) of the ultimate tensile strength; Johnson elastic limit, 44,000 lb. per sq. in. or 72 per cent. of the ultimate; ultimate tensile strength, 61,400 lb. per sq. in.; modulus (Young's) of elasticity, 17,500,000.

A series of stress-strain curves on annealed, half-hard, and hard copper wires was published in 1904 by Mr. F. O. Blackwell in a paper entitled "Conductors for Long Spans," Trans. International Elec. Cong., St. Louis, 1904, Vol. II, p. 331.

Fig. 6 shows a stress-strain diagram, from Mr. Blackwell's paper, for hemp-centre, hard-drawn, concentric-lay, copper cable composed of six 0.168-in. strands. The curve *A* is for the cable, and *B* for one of the strands. The elastic behavior is notably different from that of solid wire, since the actual elongation of a new or previously unstressed cable appears to comprise two components, one due to tightening or readjustment of the outer strands around the core, and the other to actual stretching of the material.

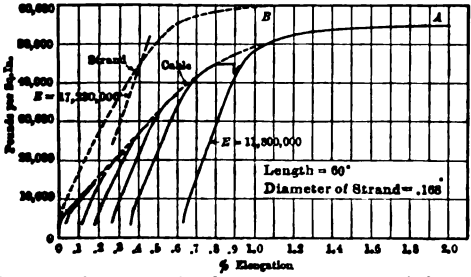


FIG. 6.—Stress-strain curve for hemp-centre, concentric-lay, six-strand, hard-drawn copper cable.

71. Elastic limit and yield point. The stress-strain curves for annealed copper show that it has no very definite elastic limit and in fact commences to set (flow under stress) at comparatively low stresses; it also has no yield point, *i.e.*, a point at which a marked increase in elongation suddenly takes place with little or no increase in load. Copper of medium or of full hardness behaves differently and exhibits a fairly definite elastic limit, but no yield point.

The rate of application of the load also plays an important part in the results. When given sufficient time, hard copper takes a set before it reaches the elastic limit. In the strictest meaning of the term, copper probably has no absolutely definite elastic limit whatever. What is ordinarily meant by elastic limit is the value obtained in tests made in a specified manner and at a definite rate of loading, such as outlined by the American Society for Testing Materials. The stress-strain curves also show very plainly that the ultimate elastic limit is raised by stressing the material beyond the initial elastic limit, or giving it a set.

Since annealed copper wire receives some hardening by handling, and also by stressing under ordinary safe loads, it is customary to assume that it has a fairly high elastic limit, one of the accepted values being as high as 85 per cent. of the ultimate strength.* The A. S. T. M. gives 50 per cent. average for medium hard-drawn wire; 55 per cent. average and 50 per cent. minimum for hard-drawn No. 4/0 to No. 1/0; 60 per cent. average and 55 per cent. minimum for hard-drawn No. 1 to No. 18, in terms of ultimate tensile strength required in their standard specifications.

* Report of Committee on Overhead Line Construction, N. E. L. A., 1911; p. 173 (Appendix A).

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72. Fatigue under load. Under long-sustained loads approaching th normal tensile strength, copper has somewhat less strength than the value obtained by ordinary test. Mr. F. O. Blackwell, in the paper referred to i Par. **70**, found that a 0.168-in. hard-drawn wire stressed to 54,000 lb. pe sq. in., stretched continuously, and broke in 7 days, 8 hours; pieces of th same wire afterward broke at 61,000 lb. in the testing machine. He conclude that a hard-drawn wire would stand continuously a stress of about 80 pe cent. of its normal tensile strength.

73. Young's modulus of elasticity for annealed and hard copper i not a very definitely known quantity and the values given for it fluctuat over a considerable range. This may be accounted for, in the case of anneale copper, by the lack of any very definite elastic limit, and the fact that th initial stress-strain diagram departs at a very early stage from Hooke's law and as soon as a slight load has been applied the properties commence t change. In all cases, the final value of the modulus, after stressing, i almost invariably greater than the initial modulus. The following value represent the extreme range, and a probable average, drawn from severa authorities,* expressed in in-lb. measure.

State	Range	Probable average
Annealed wire	7×10^6 to 17×10^6	12×10^6
Annealed concentric strand	5×10^6 to 12×10^6	9×10^6
Hard-drawn wire	13×10^6 to 19×10^6	16×10^6
Hard-drawn concentric strand	10×10^6 to 14×10^6	12×10^6

The Bureau of Standards gives 17×10^6 to 18×10^6 for both anneale and hard-drawn copper wire (Circular No. 73).

74. Specific heat of copper is not independent of temperature. The fo lowing values were taken from "Tables Annuelles de Constantes et Do nées Numériques de Chemie, de Physique et de Technologie" (For 191 University of Chicago Press, 1912), p. 50.

Specific heat, at −50 deg. cent	0.0862
Specific heat, at 0 deg. cent	0.0910
Specific heat, at +50 deg. cent	0.0928
Specific heat, from 2.4 to 21.6 deg. cent	0.0915
Specific heat, from 17 to 100 deg. cent	0.0925

The Bureau of Standards gives, for the range from 15 to 50 deg. cent., th expression $0.0917+0.000048\ (t-25)$; this is in terms of water at 20 de cent. Also see Bur. of Standards Circular No. 73, "Copper," p. 28. Fo values at high temperatures see Hoffman, H. O. "Metallurgy of Copper;" p.

75. Thermal conductivity of copper is a function of temperature, expressed in the for. ula $\lambda_t = \lambda_0\ (1 + \alpha t)$. The following values of therm conductivity, in g- al. (cm-cube) per sec. per deg. cent. were determined b Jaeger and Diesselhorst.†

Thermal conductivity, at 18 deg. cent	0.918
Thermal conductivity, at 100 deg. cent	0.908
Temperature coefficient, from 18 to 100 deg. cent	−0.0001

Langmuir gives 0.84 g-cal. for commercial copper and 0.92 g-cal. for pu copper. Also see Bur. of Standards Circular No. 73, "Copper," p. 26.

76. Properties of copper at very high temperatures. See a paper b Carl Hering, "The Proportioning of Electrodes for Furnaces," *Tran* A. I. E. E., Vol. XXIX (1910), pp. 485 to 545. Also covers carbo graphite and iron.

77. Specifications for copper wire, annealed, medium hard and har drawn, have been adopted by the American Society For Testing Materia

* Blackwell, F. O. "Conductors for Long Spans;" *Trans.* Internation Elec. Congress, St. Louis, 1904; Vol. II, p. 341.
Blackwell, F. O. "Long Spans for Transmission Lines;" *Trans.* A. I. E., Vol. XXIII, 1904, p. 511.
"Smithsonian Physical Tables," 5th rev. ed., 1910, p. 75.
American Steel & Wire Co.; "Handbook of Electrical Wires and Cables, 1910, p. 14.

† "Smithsonian Physical Tables," 1920, 7th rev. ed., p. 213.

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and will be found in the current issue of the "Year Book." They are too extended for reproduction.

78. Standard sections for copper trolley wire are prescribed in the specifications of the A. S. T. M. (see "A. S. T. M. Standards") and are shown in Figs. 7 and 8. These sections are known respectively as "grooved" and "figure eight." Copper trolley wires are always hard drawn, in order to secure maximum hardness and strength.



FIG. 7.—"American Standard" grooved trolley-wire sections.

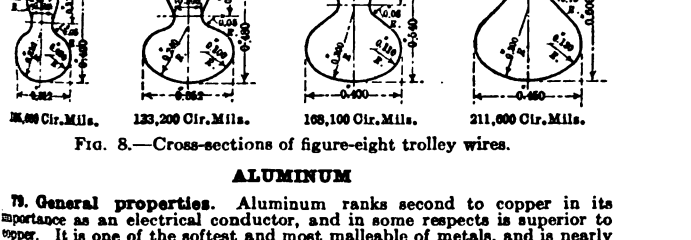


FIG. 8.—Cross-sections of figure-eight trolley wires.

ALUMINUM

79. General properties. Aluminum ranks second to copper in its importance as an electrical conductor, and in some respects is superior to copper. It is one of the softest and most malleable of metals, and is nearly white, or silver-white, in color. The density depends to some extent upon the physical state, an average value being 2.7. Aluminum melts at 658 deg. cent.* (1,216 deg. fahr.). Molten aluminum is very fluid and care should be taken not to overheat it. In the molten state it readily absorbs gases, but upon cooling these occluded gases are partially liberated, giving rise to blow holes in castings. Aluminum boils at 1,800 deg. cent. (3,272 deg. fahr.).† Like copper, aluminum can be cast, forged, rolled or drawn, and also becomes hardened by working, although it requires less annealing than copper or brass. By cold rolling and drawing it can be given considerable rigidity and temper, with accompanying increase in tensile strength. The general effect of cold or hard drawing upon aluminum is quite similar to the effect upon copper.

Aluminum when exposed to dry air is not affected, but in the presence of moist air it tarnishes rapidly, the coating consisting of oxide of aluminum (Al_2O_3) or alumina. This coating is protective, so that the corrosion is not progressive; the oxide is also very refractory, which accounts for the difficulty of soldering aluminum. Hydrochloric acid and alkaline solutions readily attack aluminum; concentrated sulphuric acid, hot dilute sulphuric acid, and hot nitric acid affect it to a less extent. Sulphur and sulphur

*Circular No. 7, "Pyrometer Testing and Heat Measurements;" Bureau of Standards, 1910; p. 4.

†Fulton, C. H. "Principles of Metallurgy;" McGraw-Hill Book Co., Inc., New York, 1910; p. 74.

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dioxide do not affect it at ordinary temperatures; it is not attacked by sul phuretted hydrogen, or carbonic acid. It resists the action of sea wate better than copper, provided there is no electrolysis, but it is a highly elec tropositive metal. The presence of impurities in considerable quantitie lowers the resistance to corrosion in marked degree. There is also dange from electrolytic corrosion if aluminum is alloyed with an electronegativ metal.

The electrical conductivity of aluminum, like that of copper, depends on it degree of chemical purity. The conductivity of hard-drawn aluminum about 2 per cent. less than that of soft or annealed aluminum. The tensil properties, in like manner, depend greatly upon the physical state, bein much improved by cold rolling and drawing.

The alloys of aluminum are very numerous. The so-called light alloy containing but small percentages of other metals, are light, hard and stron but do not resist corrosion from galvanic action. The heavy alloys, or alum num-bronzes, with but 2 per cent. to 10 per cent. of aluminum, and respec tively 98 per cent. to 90 per cent. of copper, have high tensile strength an strongly resist corrosion in air or sea water. A very small proportion aluminum, about 0.01 per cent., added to iron, steel or brass in casting re moves the oxide and prevents blow holes.

The tinning process, which is applied to copper wires intended to receiv an insulation of rubber compound (sulphur being present), is unnecessar in the case of aluminum.

Aluminum possesses an insulating film which ordinarily has a dielectr strength of about 0.5 volt, and by electrolytic action this value can b somewhat increased.

80. Commercial grades of aluminum. The impurities most com monly found in aluminum are silicon and iron. Silicon in aluminum exists two forms, one seemingly combined with aluminum as combined carbo exists in pig iron, and the other as an allotropic graphitoidal modificatio Small quantities of copper, sodium, carbon and occluded gases are als found in aluminum. The Aluminum Company of America classifies alum num commercially in three grades,* as follows:

Extra-pure aluminum, No. 1 grade or so-called pure aluminum, and No. grade for castings, or structural shapes. The average composition is follows:

	No. 1 (per cent.)	No. 2 (per cent.
Aluminum	99.55	96
Silicon	0.30	2
Iron	0.15	2

Pure aluminum (No. 1 grade or better) is necessary to secure high electric conductivity, extreme malleability, ductility and maximum resistance corrosion. For other purposes small amounts of copper, nickel, tungste manganese, chromium, titanium, zinc or tin may be advantageously added aluminum to produce hardness, rigidity and strength. These metals wh alloyed with aluminum do not diminish its resistance to corrosion so much silicon or iron. Also see Circular No. 76, "Aluminum and Its Light Alloys Bureau of Standards, 1919.

81. Typical analysis. The following analyses of aluminum are typic

	Aluminum Co. of Amer.† (per cent.)	Richard (per cent.
Aluminum	99.57	99.25
Silicon	0.29	0.64
Iron	0.14	0.04
Copper		0.02
Lead		0.01

* "Properties of Aluminum;" Aluminum Co. of America, Pittsburgh, P 1909; p. 7.

† Bureau of Standards, Circular No. 31, Third Ed., Oct. 1, 1914; p. 14.

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81. Methods of working aluminum are described at some length in a publication issued by the Aluminum Company of America.* Sections or shapes similar to those in which steel is rolled can be made of aluminum and its alloys; sheets can be rolled commercially as thin as No. 40 A.W.G. Aluminum can also be stamped, drawn, beaten, spun, forged, extruded and machined, with suitable methods, tools, dies and lubricants. Aluminum can be drawn into a great variety of forms; except for slight differences, the methods used in drawing copper wire are applicable. Like most other metals it is hardened and strengthened by working, and softened again by annealing. The annealing temperatures depend on the composition of the metal, but probably lie between the limits of 343 deg. cent. (650 deg. fahr.) and 482 deg. cent. (900 deg. cent.). Also see Circular No. 76, Bureau of Standards.

Cleaning or pickling is done by dipping first in benzene and then in hot caustic alkali (such as caustic soda or caustic potash), in nearly saturated solution. Upon removal the metal should be washed in cold running water and next immersed in a hot solution of strong nitric acid, to neutralise the caustic. Finally it should be washed in hot running water and then quickly dried in hot air; small articles should be placed in sawdust.

The ordinary low-temperature solders, containing lead, are not suitable for soldering aluminum, since the surface oxide will not dissolve under the action of a flux or salt as in the case of copper, tin, or zinc. The temperature at which solder alloys with aluminum is approximately 349 deg. cent. (660 deg. fahr.). It is first necessary to tin the surface of aluminum by heating it in a hot flame (blow-torch) and pour over it melted tin or half-and-half solder, but Richards solder is the best; meanwhile the solder should be rubbed into the surface with a fine metal brush. In this way the oxide is melted and the solder is alloyed with the aluminum. After this tinning operation is completed, the usual soldered joint may be made. Joints in bare line conductors are usually made with sleeves or with clamps (see Sec. 11). Clamps are also used for joining aluminum conductors to copper or steel conductors; sweated bushings† are employed, of suitable metal to prevent electrolytic corrosion in the joint. Also see Circular No. 78, "Solders for Aluminum," Bureau of Standards, 1919.

Aluminum rod can be readily butt-welded by merely pressing the ends together in the flame of a blowlamp. No flux is necessary for this process. It is also possible to weld aluminum by the autogenous process and this method is generally adopted for jointing plate or sheet.

It is easy to obtain quite as good a machined surface with aluminum as any other metal. Lubricants should be used only for drilling and screwing and then only paraffin. Filing should be done with a single cut file as cross-cut files are readily clogged. Aluminum will take and retain a very high polish, fully equal to that of silver.

83. Density. The value for the density of commercial hard-drawn aluminum, accepted by the Bureau of Standards,‡ is 2.70. The Aluminum Company of America gives 2.56 for pure cast aluminum, 2.66 for annealed wire and sheets, and 2.68 for unannealed wire and sheets. The British Aluminum Company, Ltd., gives 2.56 to 2.60 for castings, and 2.71 for rolled or drawn aluminum. The Smithsonian Physical Tables (5th rev. ed., p. 85) give 2.56 to 2.58 for castings and 2.65 to 2.80 for wrought aluminum. The Encyclopædia Britannica (ed. of 1910, Vol. I, p. 771) gives 2.583 for castings and 2.688 for rolled aluminum at 4 deg. cent. Mr. H. W. Buck§ gives 2.68 for aluminum wire.

The best average value from the foregoing authorities seems to be 2.57 for castings and 2.69 for sheets or wire. The latter value is in close agreement, for engineering purposes, with the value 2.70 used by the Bureau of Standards and taken as the basis of the aluminum wire tables in this section (Par. 91). A density of 2.70 g. per cu. cm. corresponds to 0.09755 lb. per cu. in.

84. Resistivity. Much less has been published about the effect of impurities on the conductivity of aluminum than in the case of copper. The

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*"Methods of Working Aluminum;" Aluminum Co. of America, Pittsburgh, Pa., 1909.

†"Instructions for Installation and Maintenance of Aluminum Electrical Conductors;" Aluminum Company of America.

‡Circular No. 31; "Copper Wire Tables"; 1914; Third Edition, p. 14.

§Buck, H. W. "The Use of Aluminum as an Electrical Conductor;" Trans. Int. Elec. Congress, St. Louis, 1904; Vol. II, p. 313.

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ordinary percentage of impurities in commercially pure aluminum, No. grade (see Par. 80), is 0.45 per cent. In terms of the British standard fo hard-drawn copper at 60 deg. fahr. (15.6 deg. cent.) Mr. Burkewood We bourn stated* that a (volume) conductivity of 60 per cent. corresponds t 0.71 per cent. of impurities, and a conductivity of 61.7 per cent. correspond to 0.5 per cent. of impurities.

The Aluminum Company of America states† that the electrical (volume conductivity of pure (No. 1 grade) aluminum is about 62 per cent. in the Mat thiessen standard scale. The British Aluminum Company, Ltd., give (June, 1914) the following values of resistivity, expressed in microhm-cm.

	Annealed	Hard-drawn
Volume resistivity, microhm-cm. at 60 deg. fahr...	2.770	2.870
Volume resistivity, microhm-cm. at 32 deg. fahr...	2.610	2.70

The Bureau of Standards‡ gives the following average values of resistivit for commercial hard-drawn aluminum.

Mass resistivity, ohms (meter, gram), at 20 deg. cent.	0.076
Mass resistivity, ohms (mile, pound), at 20 deg. cent.	436.0
Mass per cent. conductivity	200.7
Volume resistivity, microhm–cm., at 20 deg. cent.	2.828
Volume resistivity, microhm–in., at 20 deg. cent.	1.113
Volume per cent. conductivity	61.0
Density, g. per cu. cm.	2.70
Density, lb. per cu. in.	0.097

These values given by the Bureau of Standards are the basis of the alumi num wire tables in Par. 87. Since aluminum is very rarely used as a electrical conductor in the soft state, the foregoing values given by the Bureau of Standards, for hard-drawn wire, have the most commercial significance Annealed aluminum, however, is used abroad for the conductors of under ground cables.

86. Temperature coefficient of resistance. On the authority of the British Aluminum Company, Ltd., the temperature coefficient of resistance of aluminum, for constant mass, varies from 0.0032 to 0.0040 per deg cent. and from 0.0018 to 0.0022 per deg. fahr.

A determination made in the laboratory of the Westinghouse Electric and Manufacturing Company, under the direction of Prof. Charles F. Scott, gave as the average coefficient between 0 deg. and 50 deg. cent., the value 0.0038 per deg. cent.; in the fahrenheit scale the equivalent of this value is 0.0021 per deg. Prof Scott's determination is quoted by the Aluminum Company of America.

The Bureau of Standards gives 0.0039 per deg. cent. at 20 deg. cent (Circular No. 76, 1919, p. 17.)

87. Aluminum wire tables. The complete tables for aluminum wi given in Par. 87 were taken from circular No. 31, Third Edition, issued b the Bureau of Standards, and are based on a volume conductivity, in terms o the annealed copper standard, equal to 61.0 per cent.

Aluminum wire is practically never used in single strands for overhea construction, but the tables are very useful in computing the resistance o concentric strand. In commercial practice the aluminum delivered und contract varies in conductivity from 60 per cent. to 62 per cent. of the form Matthiessen standard, many contracts being placed at 61 per cent.

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* Welbourn, B. "Insulated and Bare Copper and Aluminum Cables fo the Transmission of Electrical Energy, with Special Reference to Mini Work;" *Trans.* (British) Institution of Mining Engineers; 1913. Giv bibliography on aluminum wire.

† "Properties of Aluminum;" Aluminum Company of America, Pittsburg Pa., 1909; p. 27.

‡ Circular No. 31, "Copper Wire Tables;" 1914; Third Edition, p. 14.

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87. Table of hard-drawn aluminum wire at 20 deg. cent.
English Units: American Wire Gage (B. & S.)

Gage No.	Diameter in mils	Cross-section: Circular mils	Cross-section: Square inches	Ohms per 1000 feet	Pounds per 1000 feet	Pounds per ohm	Feet per ohm
0000	460.	212000.	0.166	0.0804	195.	2420.	12400.
000	410.	168000.	0.132	0.101	154.	1520.	9860.
00	365.	133000.	0.105	0.128	122.	957.	7820.
0	325.	106000.	0.0829	0.161	97.0	602.	6200.
1	289.	83700.	0.0657	0.203	76.9	379.	4920.
2	258.	66400.	0.0521	0.256	61.0	238.	3900.
3	229.	52600.	0.0413	0.323	48.4	150.	3090.
4	204.	41700.	0.0328	0.408	38.4	94.2	2450.
5	182.	33100.	0.0260	0.514	30.4	59.2	1950.
6	162.	26300.	0.0206	0.648	24.1	37.2	1540.
7	144.	20800.	0.0164	0.817	19.1	23.4	1220.
8	128.	16500.	0.0130	1.03	15.2	14.7	970.
9	114.	13100.	0.0103	1.30	12.0	9.26	770.
10	102.	10400.	0.00815	1.64	9.55	5.83	610.
11	91.	8230.	0.00647	2.07	7.57	3.66	484.
12	81.	6530.	0.00513	2.61	6.00	2.30	384.
13	72.	5180.	0.00407	3.29	4.76	1.45	304.
14	64.	4110.	0.00323	4.14	3.78	0.911	241.
15	57.	3260.	0.00256	5.22	2.99	0.573	191.
16	51.	2580.	0.00203	6.59	2.37	0.360	152.
17	45.	2050.	0.00161	8.31	1.88	0.227	120.
18	40.	1620.	0.00128	10.5	1.49	0.143	95.5
19	36.	1290.	0.00101	13.2	1.18	0.0897	75.7
20	32.	1020.	0.000802	16.7	0.939	0.0564	60.0
21	28.5	810.	0.000636	21.0	0.745	0.0355	47.6
22	25.3	642.	0.000505	26.5	0.591	0.0223	37.8
23	22.6	509.	0.000400	33.4	0.468	0.0140	29.9
24	20.1	404.	0.000317	42.1	0.371	0.00882	23.7
25	17.9	320.	0.000252	53.1	0.295	0.00555	18.8
26	15.9	254.	0.000200	67.0	0.234	0.00349	14.9
27	14.2	202.	0.000158	84.4	0.185	0.00219	11.8
28	12.6	160.	0.000126	106.	0.147	0.00138	9.39
29	11.3	127.	0.0000995	134.	0.117	0.000868	7.45
30	10.0	101.	0.0000789	169.	0.0924	0.000546	5.91
31	8.9	79.7	0.0000626	213.	0.0733	0.000343	4.68
32	8.0	63.2	0.0000496	269.	0.0581	0.000216	3.72
33	7.1	50.1	0.0000394	339.	0.0461	0.000136	2.95
34	6.3	39.8	0.0000312	428.	0.0365	0.0000854	2.34
35	5.6	31.5	0.0000248	540.	0.0290	0.0000537	1.85
36	5.0	25.0	0.0000196	681.	0.0230	0.0000338	1.47
37	4.5	19.8	0.0000156	858.	0.0182	0.0000212	1.17
38	4.0	15.7	0.0000123	1080.	0.0145	0.0000134	0.924
39	3.5	12.5	0.00000979	1360.	0.0115	0.00000840	0.733
40	3.1	9.9	0.00000777	1720.	0.0091	0.00000528	0.581

88. Aluminum cable tables are given in Par. **89**. The values of resistance and weight per 1,000 ft. are 2 per cent. greater than for a solid rod equal to the combined cross-sections of the wires of the cable; this increment corresponds to a pitch of 15.7. The component wires are assumed to have the same value of resistivity as the hard-drawn aluminum in Par. **87**, temperature differences being allowed for. See Par. **55** to **59** on the general properties of concentric strands.

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88a. Table of hard-drawn steel-core aluminum cable

(Aluminum Company of America)

Size		Copper equivalent	Usual stranding		Diameter overall (in.)	Weight, lb. per mile			Elastic limit (lb.)	Ultimate strength (lb.)	Ohms per 1,000 ft.
A. W. G. No.	Circular mils		Aluminum	Steel		Aluminum	Steel	Total			
.....	605,000	380,500	54×0.1059	7×0.1059	0.953	2,999	1,119	4,118	14,675	21,270	0.0286
.....	500,000	314,500	30×0.1291	19×0.0775	0.904	2,477	1,625	4,102	17,140	23,750	0.0347
.....	336,400	0000	30×0.1059	7×0.1059	0.741	1,669	1,119	2,788	11,715	16,200	0.0515
.....	266,800	000	6×0.2108	7×0.0705	0.633	1,319	492	1,811	6,470	9,385	0.0648
0000	211,600	00	6×0.1880	1×0.1880	0.564	1,052	504	1,556	5,940	8,435	0.0816
000	167,805	0	6×0.1670	1×0.1670	0.501	830	397	1,227	4,960	6,660	0.1026
00	133,079	1	6×0.1490	1×0.1490	0.447	660	317	977	3,730	5,300	0.1294
0	105,534	2	6×0.1327	1×0.1327	0.398	525	251	776	2,960	4,200	0.1639
1	83,694	3	6×0.1182	1×0.1182	0.355	417	200	617	2,355	3,340	0.2070
2	66,373	4	6×0.1052	1×0.1052	0.316	330	158	488	1,860	2,660	0.2610
3	52,634	5	6×0.0938	1×0.0938	0.281	262	125	387	1,480	2,100	0.3291
4	41,742	6	6×0.0834	1×0.0834	0.250	207	99	306	1,170	1,665	0.4150
5	33,102	7	6×0.0743	1×0.0743	0.223	164	79	243	930	1,315	0.5217
6	26,250	8	6×0.0661	1×0.0661	0.198	130	62	192	735	1,045	0.6577
7	20,816	9	6×0.0586	1×0.0586	0.176	102	49	151	575	820	0.8293
8	16,509	10	6×0.0525	1×0.0525	0.158	82	39	121	465	660	1.045

This table is based on the following constants: Elastic limit of aluminum, 14,000 lb. per sq. in.; elastic limit of steel, 130,000 lb. per sq. in.; ultimate strength of aluminum, 24,000 lb. per sq. in.; ultimate strength of steel, 160,000 lb. per sq. in.; for stranded conductors, the elastic limits and the ultimate strengths are taken as the sum of the corresponding values for the individual strands; volume conductivity of aluminum, 61 per cent.

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89. Table of bare concentric-lay cables of hard-drawn aluminum
(English Units)

Circular mils	A.W.G. No.	Ohms per 1,000 ft.		Pounds per 1,000 ft.	Concentric stranding		
		25 deg. cent. (77 deg. fahr.)	65 deg. cent. (149 deg. fahr.)		No. of wires	Diam. of wires in mils	Outside diam. in mils
1,000,000		0.0177	0.0204	938.	37	164.4	1151
900,000		0.0197	0.0227	844.	37	156.0	1092
800,000		0.0221	0.0255	750.	37	147.0	1029
700,000		0.0253	0.0291	657.	37	137.5	963
600,000		0.0295	0.0340	563.	19	177.7	890
500,000		0.0354	0.0408	469.	19	162.2	810
400,000		0.0442	0.0510	375.	19	145.1	725
300,000		0.0590	0.0680	281.	19	125.7	630
300,000		0.0590	0.0680	281.	7	207.0	621
250,000		0.0707	0.0816	235.	7	188.9	567
212,000	0000	0.0834	0.0962	199.	7	174.0	522
168,000	000	0.1053	0.1214	158.	7	154.9	465
133,000	00	0.1330	0.1533	125.	7	137.8	414
106,000	0	0.1668	0.1924	99.4	7	123.1	369
83,700	1	0.2113	0.2436	78.5	7	109.3	327
66,400	2	0.2663	0.3071	62.3	7	97.4	292
52,600	3	0.3362	0.3876	49.3	7	86.7	260
41,700	4	0.4241	0.4890	39.1	7	77.2	232
33,100	5	0.5343	0.6160	31.0	7	68.8	206
26,300	6	0.6724	0.7753	24.7	7	61.3	184

90. Steel-core aluminum cable is a concentric strand consisting of a central core of galvanized steel wires with one or more layers of aluminum wire outside. The effect of the steel core is to improve the tensile properties of the cable and lower the temperature coefficient of expansion. The British Aluminum Company, Limited, is the authority for the following properties of cables of this type.

	Aluminum (individually)	Steel (individually)	Aluminum-steel cable		
			1 steel 6 aluminum	7 steel 30 aluminum	7 steel 54 aluminum
Elastic limit	14,000	110,000	.....	.....	.....
Tensile strength	24,000	160,000	47,000	53,100	48,100
Young's modulus	9×10^6	30×10^6	12×10^6	13×10^6	11.4×10^6
Coefficient of expansion per deg. fahr	12.8×10^{-6}	6.4×10^{-6}	10.51×10^{-6}	10×10^{-6}	10.87×10^{-6}

The properties of cables of different sizes, of this type, are given in Par. **88a**.

91. Coefficient of linear expansion. The value given by Sir Roberts-Austen for the linear coefficient of expansion is 0.0000231 per deg. cent. from 0 to 100 deg. cent.; the corresponding value per deg. fahr. is 0.0000128. The value per deg. cent. given by the British Aluminum Company is 0.0000234. The 7th revised edition (1920) of the "Smithsonian Physical Tables" (Fowle, F. E.) gives the coefficient as 0.00002313 at 40 deg. cent.

92. Tensile strength. The tensile strength of aluminum depends upon its state, previous working and heat treatment. The strength of aluminum is increased by cold working, as in the case of copper. The approximate range of tensile strength of aluminum in various forms is given next below, in lb. per sq. in. (Aluminum Co. of America).

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Castings	12,000 to 14,00
Sheets	24,000 to 40,00
Bars	28,000 to 40,00
Wire	25,000 to 55,00

The tensile strength of aluminum wire, in the sizes used commercially ranges from 14,000 to 33,000 lb. per sq. in., depending upon the size of th wire and upon its mechanical and heat treatments. **Hard-drawn** aluminu wire, in the sizes usually employed in the construction of concentric cable ranges from about 23,000 to 27,000 lb. per sq. in. It is possible to produc hard-drawn wire of greater strength than this, but it is likely to be "short or brittle and is not satisfactory commercially.

The British Aluminum Company, Ltd., gives the following table showin the strength of progressive sizes of hard-drawn wire, which is practicall the same as the range stated by the Aluminum Company of America.

S.W.G. No.	Diam. (in.)	Tensile strength (lb. per sq. in.)	S.W.G. No.	Diam. (in.)	Tensile strength (lb. per sq. in.)
7/0	0.500	22,000	10	0.128	25,000
5/0	0.400	23,000	12	0.104	26,000
0	0.324	23,000	14	0.080	27,000
2	0.276	23,000	16	0.064	28,000
4	0.232	24,000	18	0.048	29,000
6	0.192	24,000	20	0.036	32,000
8	0.160	25,000	.....	.....	.....

Soft or annealed aluminum is never used in overhead spans, but is used t some extent for underground cables.

Concentric cables have a breaking strength somewhat less the sum of th breaking strengths of the strands, not usually exceeding 85 to 90 per cen of the latter. Theoretically the strength of concentric-lay cable is a functio of the pitch.

93. Elastic limit. Under the definition of Hooke's law, aluminu has no definite elastic limit, because it stretches under load, if the load is hel constant for any appreciable length of time. See stress-strain diagrams i Figs. 9 and 10. Taking as the definition of elastic limit, the maximum loa under which the material will not continue to stretch, it can be stated tha the elastic limit of hard-draw wire will range from abou 12,000 to 17,000 lb. per sq. in or from 50 to 60 per cent. the ultimate tensile strength.

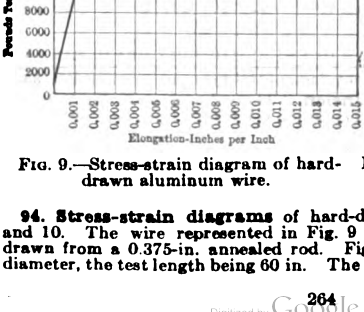


FIG. 9.—Stress-strain diagram of hard-drawn aluminum wire.

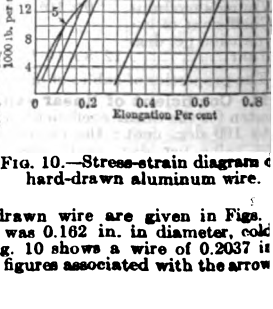


FIG. 10.—Stress-strain diagram o hard-drawn aluminum wire.

94. Stress-strain diagrams of hard-drawn wire are given in Figs. and 10. The wire represented in Fig. 9 was 0.162 in. in diameter, cold drawn from a 0.375-in. annealed rod. Fig. 10 shows a wire of 0.2037 i diameter, the test length being 60 in. The figures associated with the arrow

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indicate the number of minutes the load was held at each of several points. This specimen broke at 23,900 lb. per sq. in., with an elongation of 1.25 per cent.

96. Elongation at rupture. The total elongation at rupture, for hard-drawn wire in commercial sizes, ranges from about 2 to 4 per cent.

96. Young's modulus of elasticity in tension ranges from 8,000,000 to 12,000,000, with an average of 9,000,000 to 10,000,000. F. O. Blackwell gives the modulus for concentric cables as 7,500,000 (Trans. Int. Elec. Cong., St. Louis, 1904, Vol. II, pp. 331–347).

97. Specific heat of aluminum at 0 deg. cent. is 0.2089 and at 100 deg. cent. is 0.2226; the mean specific heat between 16 and 100 deg. cent. is 0.2122 (5th rev. ed., "Smithsonian Phys. Tables," p. 228).

98. Thermal conductivity of aluminum at 18 deg. cent. is 0.504 gram-calorie (cm-cube) per deg. cent. per sec. (Circular No. 76, Bureau of Standards, 1919).

99. Aluminum bars are used in power-plant switchboard connections for bus bars, and for carrying very large currents in electrolytic work. Since bus bars are generally designed to have a stated carrying capacity limited by a stated temperature rise, the comparative cross-sections of aluminum and copper are not required in practice to be in inverse ratio to the respective conductivities, because of the difference in radiating surface.

COPPER-CLAD STEEL

100. Compound or bi-metallic wires composed of copper-covered iron or steel have been manufactured by a number of different methods, and were first attempted many years ago. Aluminum-covered steel has also been tried, on an experimental scale. The general object sought in the manufacture of such wires is the combination of the high conductivity of copper or aluminum with the high strength and toughness of iron or steel. The resulting conductor is obviously a compromise between copper (or aluminum) and iron, being inferior as a whole to the former and superior to the latter.

101. Union between the metals. In the early attempts to produce bi-metallic wires, the two metals were not welded, but merely in physical contact. Difficulties were sometimes experienced from electrolytic corrosion of the iron, more particularly at points where both metals were loosely exposed, as might occur at joints. No great success attended the use of such wires until modern processes were developed for effecting a weld or molecular union between the metals, to give greater stability and strength to the copper coating and prevent electrolysis.

102. Manufacturing process. Copper-clad steel wire has been manufactured, in this country, by three different methods, known as the Monnot process (formerly used by the Duplex Metals Co.), the Griffith process (Colonial Steel Co.) and the Roth process (Copper Clad Steel Co.), the first of which is not present in commercial use.

The Griffith process consists briefly of coating a mild steel billet with copper by electrolytic deposition (Sec. 19), then inserting the copper-coated billet in a copper tube, closing the ends, and heating the compound billet preparatory to rolling; it is then hot-rolled to rods, and cold-drawn to wire.

The Roth process consists of coating a mild steel billet with a special flux, placing it in an upright mold closed at the bottom, heating the billet and mold to yellow heat and then casting molten copper around the billet, after which it is hot-rolled to rods and cold drawn to wire.

103. Commercial grades of copper-clad steel wire. It has become customary commercial practice to rate copper-clad steel wire in terms of the ratio of its volume conductivity to copper. Thus one manufacturer makes two grades of wire, having respectively 30 per cent. and 40 per cent. conductivity ratio to copper; another manufacturer has standardized a 30-per cent. wire. These ratios are usually average ratios, and in practice certain tolerance limits must be recognized, above and below the average; or else the rated conductivity can be specified as the absolute acceptable minimum.

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104. Table of hard-drawn copper-clad steel wire

(Copper-Clad Steel Co.)

Size A. W. G. No.	Diam. (in.)	Circular mils	Average weight		Approx. breaking load (lb.)	Average resistance at 68 deg. fahr.			
						Per 1,000 ft.		Per mile	
			Lb. per 1,000 ft.	Lb. per mile		30% grade	40% grade	30% grade	40% grade
0000	0.460	212,000	585.0	3,089.0	9,850	0.165	0.124	0.871	0.655
000	0.410	168,000	467.0	2,466.0	8,290	0.208	0.156	1.098	0.824
00	0.365	133,000	370.0	1,954.0	6,845	0.262	0.197	1.38	1.04
0	0.325	106,000	293.0	1.547.0	5,695	0.331	0.248	1.75	1.31
1	0.289	83,700	231.0	1,220.0	4,800	0.421	0.316	2.22	1.67
2	0.258	66,400	184.0	971.0	3,975	0.531	0.398	2.80	2.10
3	0.229	52,600	146.0	771.0	3,200	0.670	0.503	3.54	2.66
4	0.204	41,700	116.0	614.0	2,610	0.844	0.633	4.46	3.34
5	0.182	33,100	92.0	485.0	2,190	1.06	0.799	5.60	4.23
6	0.162	26,300	73.0	385.0	1,800	1.34	1.01	7.08	5.33
7	0.144	20,800	58.0	308.0	1,450	1.69	1.27	8.92	6.71
8	0.128	16,500	46.0	242.0	1,200	2.13	1.60	11.3	8.45
9	0.114	13,100	37.0	195.0	970	2.69	2.02	14.2	10.7
10	0.102	10,400	29.0	154.0	800	3.39	2.55	17.9	13.5
11	0.091	0,230	23.0	121.0	645	4.28	3.21	22.6	16.9
12	0.081	6,530	18.0	96.0	520	5.39	4.05	28.5	21.4
13	0.072	5,180	14.4	76.0	415	6.80	5.11	35.9	27.1
14	0.064	4,110	11.6	61.0	330	8.58	6.44	45.3	34.0
15	0.057	3,260	8.99	47.5	275	10.8	8.13	57.0	42.9
16	0.051	2,580	7.23	38.2	210	13.7	10.2	72.3	53.9
17	0.045	2,040	5.68	30.0	170	17.2	12.9	90.8	68.1
18	0.040	1,620	4.45	23.5	140	21.7	16.3	114.0	86.1
19	0.035	1,290	3.54	18.7	110	27.4	20.5	145.0	108.0
20	0.032	1,020	2.80	14.8	90	34.5	25.9	182.0	137.0

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102. Table of Copper-Clad Steel Concentric-lay Cables
(Copper-Clad Steel Co.)

Approx. diam.	Diam. of each strand	Actual diam.	Total cross-section	Weight		Approx. breaking load	Average resistance per 1,000 ft. at 68 deg. fahr.	
Inches	Inches	Inches	Circ. mils	Pounds per 1,000 ft.	Pounds per mile	Pounds	30 per cent. grade	40 per cent. grade
							Ohms	Ohms
Seven strand								
$\frac{3}{8}$	0.204	0.612	291,310	836	4,434	16,440	0.124	0.093
$\frac{11}{32}$	0.182	0.546	231,870	653	3,497	13,800	0.160	0.118
$\frac{1}{4}$	0.162	0.486	183,710	526	2,775	11,340	0.197	0.148
$\frac{7}{32}$	0.144	0.432	145,150	418	2,221	9,140	0.248	0.186
$\frac{9}{32}$	0.128	0.384	114,690	332	1,745	7,560	0.313	0.236
$\frac{5}{32}$	0.102	0.306	72,830	209	1,110	5,040	0.499	0.375
$\frac{1}{4}$	0.081	0.243	45,930	129	692	3,280	0.793	0.597
Nineteen strand								
1	0.204	1.020	790,700	2,270	12,035	44,630	0.0457	0.0343
$\frac{7}{32}$	0.182	0.900	629,360	1,800	9,491	37,450	0.0581	0.0432
$\frac{13}{64}$	0.162	0.810	498,640	1,439	7,534	30,780	0.0726	0.0546
$\frac{3}{16}$	0.144	0.720	393,980	1,135	6,028	24,795	0.0915	0.0688
$\frac{11}{64}$	0.137	0.685	366,610	1,018	5,332	22,660	0.103	0.0777
$\frac{9}{64}$	0.128	0.640	311,300	900	4,736	20,520	0.115	0.0868
$\frac{9}{128}$	0.114	0.570	246,920	724	3,816	16,590	0.145	0.109
$\frac{1}{8}$	0.102	0.510	197,680	568	3,014	13,680	0.183	0.138
$\frac{7}{128}$	0.091	0.455	157,340	450	2,368	11,030	0.232	0.174
$\frac{5}{64}$	0.072	0.360	98,500	281	1,487	7,100	0.368	0.277
$\frac{9}{128}$	0.064	0.320	77,820	226	1,194	5,640	0.464	0.349

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106. Properties of copper-clad steel wire depend upon the relativ proportions of copper and steel, the constituents of the latter, the mechanic treatment and the heat treatment. The cold-drawing process hardens th steel core to an unpermissible degree and it becomes necessary at interva to anneal it before proceeding further with the drawing process. The com mercial grades are obtainable either dead soft (annealed) or hard drawn, s desired. The properties of the commercial grades of wire are given i Par. **104** and **105**, taken from the manufacturers' tables. In drawing specif cations it is customary to fix tolerance limits, or else minimum (or maximum limits. For technical articles dealing with the properties of copper-cla steel wire, see the following: *Electrical World*, Vol. LII, pp. 701 and 81 *Scientific American*, Vol. XCVIII, p. 347; *Iron Age*, Vol. LXXVII, p. 52 *Journal of Industrial and Engineering Chemistry*, Sept., 1909; *Electric World*, Dec. 22, 1910, Dec. 29, 1910 and Jan. 12, 1911; *Telephone Enginee* Oct., 1910 to July, 1911, inclusive. Proceedings A. S. T. M., Vol. X, pp 280–294; *Telephone Engineer*, Dec., 1911 to Mar., 1912, inclusive.

107. Temperature coefficient of resistance of the 40 per cent. grade copper-clad steel is approximately 0.0045 per deg. cent., from and at ser The coefficient ranges from about 0.004 to 0.005, depending apparently upo the constituents of the wire and its physical condition.

108. Permeability of steel core is about 70, for small magnetizing force at 800 cycles per sec.; at power frequencies it is from 100 to 125. Th maximum permeability will be from 600 to 800 at roughly 5,000 gausse The measured hysteresis loss in the core of No. 1 A.W.G. wire, at 10,0 gausses (max.), was 15,000 ergs per cu. cm. per cycle. The resistivity of t steel will range from 12 to 13 microhm-cm. at 20 deg. cent., approximatel For method of calculating internal inductance see *Electrical World*, 1910, V LVI, p. 1521.

109. Coefficient of linear expansion of the 40 per cent. grade of coppe clad steel is 0.0000129 per deg. cent.

110. The density or specific gravity of copper-clad steel depends on t relative proportions of copper and steel. The 40 per cent. grade has a de sity of 8.2.

111. Tensile strength of copper-clad steel depends in great measu upon the kind and condition of steel in the core. The strength of the whc wire will range as high as 80,000 to 100,000 lb. per sq. in., hard-drawn. T typical **stress-strain diagram** is similar to the curve for hard-drawn copp in Fig. 5. The breaking loads are given in the tables, Par. **104** and 10

112. Young's modulus ranges from 19×10^6 to 21×10^6 lb. per sq. i for hard-drawn wire and 16×10^6 to 20×10^6 for concentric cable.

113. Specifications for copper-clad steel wire will be found in t "Manual" of the Railway Signal Division, American Railway Associatic Also see "Handbook of Overhead Line Construction," N. E. L. A.

IRON AND STEEL

114. General properties of iron and steel are covered in detail in anoth portion of this section, under "Structural Materials." The so-called ir wire is usually steel, containing carbon, manganese and silicon. The eff of these constituents on the resistivity is discussed in Par. **115**. In gener those elements which increase the tensile strength of steel also increase resistivity; similarly, the mechanical and heat treatments which incre the strength, again increase the resistivity.

115. Resistivity of iron. The researches of Barrett, Brown and H field (Scient. Trans. Royal Dublin Soc., VII, Ser. 2, part 4, 1900; Jo Inst. Elec. Eng., 31, p. 674, 1902) on the electrical and magnetic propert of iron and iron alloys are especially important. They found that Swed charcoal iron containing 99.85 per cent. iron had a resistivity of 1 microhm-cm.

These investigators also found that 1 per cent. of any element added pure iron increased its specific resistance by an amount approximat proportional to the specific heat or inversely proportional to the ato weight of the alloying element.

Yensen gives the following values for different grades of annealed i (see Bulletin No. 72, Eng. Exp. Sta., Univ. of Ill.), in microhm-cm. at 20 d cent.

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Electrolytic iron melted in *vacuo*	**9.96**
Swedish charcoal iron remelted in *vacuo*	**10.30**
Commercial grades:	
Swedish charcoal iron cut from plate	**10.57**
Standard transformer steel	**11.09**
Silicon (4 per cent.) steel	**51.15**

Hopkinson tested and analyzed 35 different samples of iron (Phil. Trans. p. 463, Part II, 1885) and found resistivities (microhm-cm.) ranging from 13.78 for wrought iron to 100 for cast iron.

Also see Boudouard, O. "Electric Resistivity of Special Steels," IX, 6, No. 10, Sixth Congress Int. Assoc. for Testing Materials, New York City, 1912.

116. Preece's tests on resistivity of annealed iron wire
(Munroe and Jameson)

	Composition						Ohms (mile, lb.) at 60 deg. fahr.
	Fe	C	Mn	Si	S	P	
Swedish charcoal iron	99.70	0.10	0.03	Trace	0.022	0.045	4502
Swedish charcoal iron	99.44	0.15	0.234	0.018	0.019	0.058	4820
Siemens-Martin steel	99.60	0.10	0.324	Trace	0.035	0.034	5308
Best puddled iron	99.11	0.10	0.234	0.09	0.03	0.218	5974
Bessemer steel, soft	98.74	0.15	0.72	0.018	0.092	0.077	6163
Bessemer steel, hard	98.20	0.44	1.296	0.028	0.126	0.103	7468
Best cast steel	97.41	0.62	1.584	0.06	0.074	0.051	8033

117. Effects of different alloying elements upon the resistivity of pure iron were found by Barrett to be as follows: the values given in the table represent the increase in resistivity (microhm-cm.) resulting from the addition of 1 per cent. of different alloying elements.

Tungsten	2.0	Carbon	5.0
Cobalt	3.0	Manganese	8.0
Nickel	3.5	Silicon	13.0
Chromium	5.0	Aluminum	14.0

118. Temperature coefficient of resistance. The average coefficient per deg. cent., between 0 and 100 deg. cent., based on the measurements by Dewar and Fleming, is 0.00622. This value compares with 0.00635 based on measurements published by the Bureau of Standards (Scientific Paper No. 236). The mean value between 0 and 20 deg. cent., determined by Dewar and Fleming, is 0.00527 per deg. cent.

119. Ingot iron. The properties of American ingot iron wire are stated by the Page Steel & Wire Co. as follows, based on a series of tests of wire samples of different sizes: Resistivity, 4,800 ohms (mile, lb.); density, 7.79; temperature coefficient of resistance, from and at 20 deg. cent., 0.0055 per deg. cent.; tensile strength, 55,000 lb. per sq. in.; Young's modulus, 23×10^6; temperature coefficient of linear expansion, from and at zero deg. cent., 0.0000116 per deg. cent. The manufacturers guarantee that the total content of carbon, manganese, silicon and other impurities is not in excess of 0.16 per cent. Also see Par. **379.**

120. Resistivity and temperature coefficient of carbon steel. Barus and Strouhal found that the temper of carbon steel affected its electrical properties as shown below.

Temper	Resistivity, microhm-cm. at 0 deg. cent.	Temperature coefficient, per deg. cent.
Soft	15.9	0.00423
Light blue	18.4	0.00360
Blue	20.5	0.00330
Yellow	26.3	0.00280
Light yellow	28.9	0.00244
Glass hard	45.7	0.00161

See "Smithsonian Physical Tables," 5th rev. ed., 1910, p. 263.

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121. Resistivity of cast iron and cast steel. The resistivity of cas iron is about ten times that of pure iron, owing to both the combined carbo and the graphite; a value of 74.4 microhm-cm. for soft grades and 97. microhm-cm. for hard grades is given in the "Smithsonian Physical Tables, 5th rev. ed., 1910, p. 263. This authority also gives 19.1 microhm-cm. fo cast steel. The chemical composition, mechanical treatment and hea treatment affect the resistivity in a pronounced manner.

122. Ohms per mile-pound of galvanized iron (steel) wire
(Telephone and telegraph)

	Extra Best Best (E. B. B.)	Best Best (B. B.)	Steel
Roebling	4,700 to 5,000	5,600 to 6,000	6,500 to 7,00
Amer. Steel & Wire Co..	4,700 to 5,000	5,600 to 6,000	6,500 to 7,00
Amer. Elec. Works.....	4,700	5,500	6,500

Roebling gives the ultimate strength as equal to the product of the weigh in lb. per mile by the following factors: 3.0 for E. B. B.; 3.3 for B. B.; 3.7 fo Steel. The ratios used by the Amer. Steel and Wire Co. are respectivel 2.5, 2.8 and 3.0.

123. Table of galvanized iron (steel) wire
(American Steel and Wire Co.)

Size B.W.G.	Diameter in mils	Approximate weight in pounds per mile	Approximate breaking load in pounds			Resistance per mile (ohms) at 68 deg. fahr or 20 deg. cent.		
			Ex. B. B.	B. B.	Steel	Ex. B. B.	B. B.	Steel
0	340	1,655	4,138	4,634	4,965	2.93	3.50	4.0
1	300	1,289	3,223	3,609	3,867	3.76	4.50	5.2
2	284	1,155	2,888	3,234	3,465	4.20	5.02	5.8
3	259	960	2,400	2,688	2,880	5.05	6.04	7.0
4	238	811	2,028	2,271	2,433	5.98	7.15	8.3
5	220	693	1,732	1,940	2,079	7.00	8.37	9.7
6	203	590	1,475	1,652	1,770	8.22	9.83	11.4
7	180	463	1,158	1,296	1,389	10.48	12.52	14.5
8	165	390	975	1,092	1,170	12.43	14.87	17.3
9	148	314	785	879	942	15.44	18.47	21.5
10	134	258	645	722	774	18.79	22.48	26.1
11	120	206	515	577	618	23.54	28.16	32.7
12	109	170	425	476	510	28.52	34.12	39.7
13	95	129	310	347	372	37.60	44.95	52.3
14	83	99	247	277	297	48.98	58.59	68.1
15	72	74	185	207	222	65.54	78.38	91.2
16	65	61	152	171	183	79.51	95.08	110.6

124. Table of properties of steel trolley wire
(A. & J. M. Anderson Mfg. Co.)

Size A.W.G.	Weight (lb.)		Ultimate breaking load (lb.)	Resistance; ohms at 60 deg. fahr.	
	per 1,000 ft.	per mile		per 1,000 ft.	per mile
0	281	1481	6600	0.7161	3.781
00	354	1870	8300	0.5678	2.998
000	446	2357	9900	0.4500	2.376
0000	562	2966	12500	0.3574	1.888

Made in standard round and grooved sections, bare or galvanized.

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125. Permeability of iron wire. The permeability of iron or soft steel wire, in the ordinary commercial sizes, at frequencies of 60 cycles or less, is from 100 to 125; at 800 cycles, it is about 70. This applies to small magnetizing forces, such as exist within the wire due to the current flowing through it. These values hold for the steel core of copper-clad steel.

126. Steel rails. The resistivity of common rail steel varies in considerable degree, depending upon the chemical composition. Special soft steels used for third rails have resistivities ranging from 7.9 to 9 times that of copper; track rails, from 11 to 13 times that of copper. In manganese steels the ratio sometimes exceeds 30. The effective resistance of rails conveying alternating currents will be increased somewhat on account of skin effect and eddy-currents. See "Report of the Electric Railway Test Commission," Megraw-Hill Book Co., Inc., New York, 1906. Also see Par. **119.**

127. Density of pure iron is 7.86, which is fairly precise for wrought iron and steel. The National Tube Co. computes the weight of steel at 0.2833 lb. per cu. in. (489.5 lb. per cu. ft.) and iron at 2 per cent less.

128. Tensile properties of iron and steel wires. The tensile properties are dependent upon the composition of the metal from which the wire is drawn, upon the amount of working the wire has received in the process of manufacture and upon the heat treatment. For information upon the effect of the constituents of iron and steel on the tensile properties, see "Structural Materials," in another portion of this section.

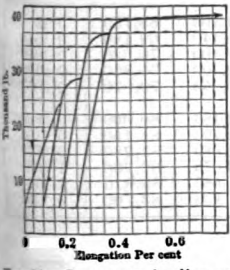


FIG. 11.—Stress-strain diagram of galvanized iron wire.

The tensile strength ranges from about 45,000 lb. per sq. in., for the purest annealed wrought iron, up to extremely high values for hard steel, in the neighborhood of 500,000 lb. per sq. in. Carbon, manganese and silicon are the chief constituents which impart strength and hardness; they also increase the electrical resistivity. Both carbon and manganese decrease the magnetic permeability.

The elastic limit and the yield point occur at about the same relative values as in structural iron and steel; in other words, the elastic ratio does not change.

Fig. 11 shows a typical stress-strain diagram; the wire was 0.164 in. in diameter and broke at 55,100 lb. per sq. in., while the elastic limit was 25,000 lb. per sq. in. and the elongation was 11 per cent. in 60 in. Time was allowed for the wire to set (see Blackwell, F. O. "Conductors for Long Spans;" Trans. Int. Elec. Cong., St. Louis, 1904, Vol. II, pp. 331–347).

Blackwell gives Young's modulus as 24×10^6 lb. per sq. in. for iron wire, 27×10^6 for steel wire, and 22×10^6 for iron and steel concentric cable. Also see Technologic Paper No. 121, "Strength and Other Properties of Wire Rope," Bureau of Standards, 1919.

129. Coefficient of expansion. Blackwell gives 0.0000064 per deg. fahr. for iron and steel wire.

130. Specific heat of wrought iron, from 15 to 100 deg. cent., is 0.115; hard-drawn iron, from 0 to 18 deg., 0.0986 and from 20 to 100 deg., 0.115 ("Smithsonian Phys. Tables," 1916).

131. Thermal conductivity of iron in gram-calories (cm-cube) per deg. cent. is 0.161 at 18 deg. cent., with a negative temperature coefficient of 0.0008 ("Smithsonian Phys. Tables," 1920).

BRONZE

132. Bronze is an alloy of copper and tin, with the addition in some cases of zinc and other metals. There are numerous varieties of bronze, some designated by a prefix indicating the special or distinguishing constituent, and others known by trade names.

133. Phosphor bronze is an alloy of copper, tin and phosphorus, containing from 2 to 6 per cent. of tin and 0.05 to 0.13 per cent. of phosphorus. Its volume conductivity is not over 35 per cent. of that of copper. Industrial bronzes carry zinc and lead, and a larger proportion of phosphorus.

134. Silicon bronze is an alloy of copper, silicon and sodium; tin and zinc

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are also added, in some cases. J. Bucknall Smith ("Wire, Its Manufacture and Uses," London, 1891) gave the following values of conductivity and tensile strength.

Conductivity (per cent.)	Tensile strength (lb. per sq. in.)	Conductivity (per cent.)	Tensile strength (lb. per sq. in.)
95	56,000	45	100,000
80	70,000	34	100,000

The grade of silicon bronze used for trolley and span wires has from 2.2 to 2.5 times the resistivity of copper and is from 35 to 70 per cent. stronger.

135. Phono-electric wire tables
(Bridgeport Brass Co.)

Size A.W.G.	Diam., mils	Weight per mile, lb.	Weight, lbs. per 1,000 ft.	Breaking load, lb.	Tensile strength, lb. per sq. in.	Resistance per 1,000 ft. in ohms, 75 deg. fahr.
0000	460.0	3,382.0	640.5	11,460	68,780	0.12
000	409.6	2,682.0	507.9	9,140	69,180	0.1518
00	364.8	2,127.0	402.9	7,400	70,620	0.1929
0	324.9	1,687.0	319.5	6,300	75,830	0.2423
1	289.3	1,338.0	253.4	5,250	79,670	0.3077
2	257.6	1,061.0	200.9	4,180	80,000	0.3868
4	204.3	668.0	126.5	2,700	81,150	0.6150
6	162.0	420.0	79.5	1,680	81,280	0.9771
8	128.5	264.0	50.0	1,075	82,700	1.555
10	101.9	166.0	31.5	685	83,810	2.472
12	80.81	105.0	19.9	420	83,700	3.932

136. Properties of bronze wires
(Perrine)

Wire	Per cent. conductivity ratio to annealed copper	Tensile strength, lb. per sq. in.	Per cent. elongation
Weiller A bronze	97.0	64,000	1
Magnesium-copper	95.2	73,000	1
Weiller B bronze	85.0	71,000	1
Magnesium-copper	81.6	87,000	1
Weiller C bronze	80.0	79,700	1
Magnesium-copper	50.2	109,000	1
American silicon bronze	38.8	79,000	2
Tempered copper	35.0	80,000	1
Weiller bronze, French telegraph	30.0	105,000	1
Phosphorus bronze	26.0	102,000	
American silicon bronze	15.8	100,000	1

Also see Parshall and Hobart, "Electric Machine Design," London, 1906; pp. 566 to 567.

137. Phono-electric wire is a copper alloy of greater tensile strength and smaller conductivity than hard-drawn copper. The manufacturers claim that it is non-corrosive and perfectly homogeneous in structure, the tensile strength being uniformly distributed over the cross-section normal to the axis of the wire. Tests on No. 0 and No. 00 A.W.G. hard-drawn copper and phono-electric to determine the fusing currents showed that the latter material fused at about 75 per cent. of the current required to fuse the former.

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phono-electric wire, on account of its high tensile properties, has been used for trolley wire and for long spans in transmission lines and in telephone and telegraph lines.

The tensile strength of hard-drawn wire ranges from 68,000 to 84,000 lb. per sq. in. The total elongation at rupture is about 1 per cent. and Young's modulus is about 18,100,000. The temperature coefficient of resistance is 0.00088 per deg. fahr. and the coefficient of linear expansion is 0.0000149 per deg. fahr.

MISCELLANEOUS METALS

138. Resistivity of various metals

(Compiled from "Smithsonian Phys. Tables," 1916)

Metal	Resistivity at 0 deg. cent. (microhm-cm.)	Temp. coef. per deg. cent., at 20 deg. cent.	Density	Therm. cond. (g-cal. per cm. cube per deg. per sec.)
Antimony	38.6	0.00389	6.62 to 6.69	0.044
Arsenic	35.0	.....	5.73	.....
Bismuth	108.0	0.00458*	9.70 to 9.90	0.019
Boron	8×10^{16}	.....	2.45 to 2.535	.....
Cadmium	6.2 to 7.0	0.0042*	8.54 to 8.67	0.22
Calcium	7.5	.....	1.54	.....
Cobalt	9.8	0.00325*	8.71	.....
Gold	2.04 to 2.09	0.00365	19.3	0.70
Indium	8.38	.....	7.28	.....
Lead	18.4 to 19.6	0.00387	11.34	0.084
Lithium	8.8	.....	0.534	.....
Magnesium	4.1 to 5.0	0.00381*	1.741	0.37
Mercury	94.07	0.00072	13.55	0.015
Nickel	6.93	0.0062*	8.60 to 8.90	0.14
Palladium	10.21	0.00354*	12.16	0.17
Platinum	10.96	0.00367*	21.37	0.16
Potassium	25.1	.....	0.870	.....
Silver	1.468	0.0040	10.4 to 10.6	1.10
Thallium	17.6	0.00398	11.86	.....
Tin	13.0	0.00365	7.30	0.15
Zinc	5.75	0.0040	7.04 to 7.19	0.26

*Average values, for range from 0 to 100 deg. cent.

139. Tungsten.* The tungsten metal of commerce, prior to the discovery of ductile tungsten, was a very hard, dark gray powder; in some cases the metal was heated with low-carbon steel in a crucible furnace, producing the alloy known as ferro-tungsten, containing 80 to 85 per cent. of tungsten. The higher-grade alloys are produced in the electric furnace. Cast tungsten is an extremely hard brittle metal, having a specific gravity of about 18.7. In 1910 a process was announced for the production of ductile tungsten, by rolling, swaging or hammering a heated body of coherent tungsten until it becomes ductile at ordinary temperatures (*Electrical World*, Jan. 10, 1914, pp. 77, 78). The melting point is 3,100 ± 50 deg. cent.

140. Ductile tungsten is a bright, tough, steel-colored metal, which can be drawn into the finest wire. The operation of wire-drawing increases the strength; Fink stated that tungsten wire of 0.0012 in. diam. had a tensile strength from 580,000 to 610,000 lb. per sq. in., and the density increased from 18.81 before drawing, to 19.30 after drawing to 0.15 in. It retains its luster almost indefinitely. Wrought tungsten has been used as a substitute for platinum contacts in electrical apparatus, for targets or anti-

*Baskerville, C. "The Chemistry of Tungsten and the Evolution of the Tungsten Lamp;" Trans. of the New York Electrical Society; New Series, No. 1; Oct. 29, 1912.

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cathodes for Röntgen tubes and for the resistor in electric heater elements; of course its most extensive application is in the form of drawn-wire filaments for incandescent lamps (Sec. 14). The processes of making ductile tungsten are described in British patent No. 2759, issued in 1910; U. S. patent No. 1,082,933 issued Dec. 30, 1913 to W. D. Coolidge. The resistivity at 25 deg. cent. is 5 microhm-cm., annealed, and 6.2 microhm-cm., hard-drawn. The mean temperature coefficient of resistance between 0 and 170 deg. cent. is 0.0051 per deg. cent. The resistance-temperature curve is given in Fig. 12. Coefficient of linear expansion, 20 to 100 deg. cent., 336×10^{-8}.

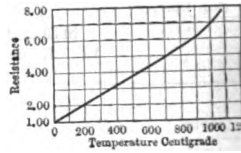


Fig. 12.—Resistance-temperature curve for tungsten.

141. Tantalum is a white lustrous metal having a specific gravity of 16.6. It is ductile and workable, and can be drawn into fine wire, in which form it has a tensile strength as high as 130,000 lb. per sq. in. The resistivity at 0 deg. cent. is 14.6 microhm-cm., and the temperature coefficient is 0.0033 per deg. cent.

142. Wood's fusible alloy contains 4 parts of bismuth, 2 parts of lead 1 part of tin and 1 part of cadmium. The melting point is 60.5 deg. cent.

143. Rose's fusible alloy contains 2 parts of bismuth, 1 part of lead, and 1 part of tin. The melting point is 93.8 deg. cent.

144. Composition and melting point of fusible alloys
(Perrine)

Composition					Melting point, deg. cent.
Tin	Bismuth	Lead	Cadmium	Mercury	
.....	20	20	.....	60	20
4	15	8	3	.....	65
1	2	1	.....	.....	98
8	8	12	.....	.....	132
50	50	.....	.....	.....	160
24	8	22	.....	.....	164
67	33	.....	.....	.....	166
80	20	.....	.....	.....	200

145. Fusing currents of different kinds of wires were investigated b W. H. Preece, who developed the formula

$$I = ad^{\frac{3}{2}} \qquad (1$$

where I is the fusing current in amperes, d is the diameter of the wire in. and a is a constant depending upon the material. He found th following values for a.

Copper.....	10,244	Iron.....	3,148
Aluminum.....	7,585	Tin.....	1,642
Platinum.....	5,172	Alloy (2Pb–1Sn).....	1,318
German silver.....	5,230	Lead.....	1,379
Platinoid.....	4,750	.....	.....

Also see Perrine, F. A. C. "Conductors for Electrical Distribution," Ne York, 1903; Chap. II.

146. Selenium is a non-metallic element chemically resembling sulph and tellurium and occurs in several allotropic forms varying in speci gravity from 4.3 to 4.8. Selenium melts at 217 deg. and boils at 690 d

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147. Table of properties of resistor wires. (See Par. 148 to 152)
(Compiled from manufacturers' data; also, Swoboda, H. O., *The Electric Journal*, May, 1913)

Material	Composition	Resistivity at 10 deg. cent.		Temp. coef. of resistance at 20 deg. cent., per deg. cent.	Thermo-electric power with copper, micro-volts at zero deg. cent	Density	Tensile strength (lb. per sq. in.)	Coefficient of linear expansion per deg. cent.	Maximum working temp. (deg. cent.)	Approx. melting point (deg. cent.)	Manufacture*
		Microhm-cm.	Ohms, mil-ft.								
Copper	Cu (annealed)	1.724	10.37	0.00393	.....	8.89	34,000	0.0000166	260	1,083	.....
Platinum	Pt	9.53	57.4	0.00367	.....	21.5	50,000	0.0000090	1,500	1,754	.....
Iron	Fe (annealed)	9.96	59.9	.....	.....	.....	.....	.....	.....	.....	.....
Nickel	Electrolytic	7.5	44.0	0.0049	.....	.....	.....	.....	600	1,450	1 & 2
Nickel, grade "A"	99% Ni	10.39	54.0	0.0041	.....	8.99	110,000	0.0000129	600	1,450	1
Nickel, grade "C"	97% Ni	13.00	80.0	0.0035	.....	.....	.....	.....	600	1,450	1
Ferro nickel alloys:											
Climax	25% Ni	87.0	536.0	0.00098	.....	8.9	75,000	0.0000171	500	.....	1
Invar	38% Ni	.....	.....	.....	.....	.....	.....	0.00000295	.....	.....	1
No. 141 alloy	70% Ni	38.0	234.0	.....	.....	.....	.....	.....	.....	.....	1
Mangaloy	Ni-Fe-Mn	113.6	700.0	0.000410	.....	.....	.....	.....	.....	.....	.....
Nickeline I	.....	43.6	262.0	0.000076	8.4	.....	.....	.....	.....	.....	6
Nickeline II	.....	33.9	204.0	0.000168	.....	8.4	.....	.....	.....	.....	6
Grade "A" metal	.....	52.8	321.0	0.000018	.....	.....	.....	.....	.....	.....	2
Krupp	Fe-Ni	85.13	512.0	0.0007	.....	8.10	85,000	.....	600	.....	3
Tico	Fe-Ni	85.9	517.0	.....	.....	.....	.....	.....	.....	.....	5
Apex	Fe-Ni	86.4	520.0	0.00054	.....	8.05	.....	.....	.....	.....	4
Superior	Fe-Ni	86.4	520.0	0.00081	.....	8.4	.....	.....	540	1,315	6
Phenix	Fe-Ni	87.0	524.0	0.00054	.....	8.09	140,000	.....	540	1,140	2

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Copper nickel alloys:											
Advance	45% Ni	53.0	326.0	1.97×10^{-1}	40.0	8.9	60,000	0.0000144	400	1,260	1
Monel	65% Ni	42.20	256–270	0.0019	.....	8.94	44,000	0.0000138	450	1,360	1 & 2
No. 300 alloy	11% Ni	16.2	100–110	0.000394	.....	.....	.....	.....	400	.....	1
Yankee silver	25% Ni	32.4	200.0	0.000155	.....	.....	.....	0.0000159	480	.....	1
18% nickel silver	Cu-Ni-Zn	32.4	200.0	0.0027	.....	8.5	70,000	0.0000173	260	.....	1
30% nickel silver	Cu-Ni-Zn	48.2	290.0	0.000200	.....	8.5	.....	.....	.....	1,160	.....
Ia Ia	Cu-Ni	49.0	295.0	0.000005	.....	8.4	.....	.....	370	1,230	6
Raymur	Cu-Ni	49.0	295.0	0.000018	.....	8.85	.....	.....	.....	.....	4
Constantin	Cu-Ni	50.0	300.0	0.000005	40.0	9.73	.....	.....	.....	.....	8
Ideal	Cu-Ni	50.0	300.0	0.000018	.....	.....	.....	.....	350	1,090	2
Nickel-iron-chromium alloys:											
Nichrome	Fe-Ni-Cr	109.0	670.0	0.00019	.....	8.15	98,000	0.0000116	950	.....	1
Nichrome II	Fe-Ni-Cr	109.0	670.0	0.000172	.....	8.02	98,000	.....	1,050	.....	1
Kromore	Ni-Cr	95.9	577.0	0.000242	.....	8.9	80,000	.....	1,100	.....	1
No. 193 alloy	Ni-Fe-Cr	85.0	523.0	0.000720	.....	8.137	60,000	0.0000171	650	.....	.....
Karma	Ni-Cr	103.0	620.0	.....	.....	.....	.....	.....	.....	.....	2
Excello	Ni-Cr	91.3	550.0	0.00016	.....	8.9	.....	.....	1,090	1,650	6
Calido	Ni-Cr	95.5	575.0	0.00034	.....	.....	160,000	.....	1,090	1,540	2
Tophet	Ni-Cr	96.0	580.0	.....	.....	8.26	.....	.....	.....	.....	4
Calorite	Ni-Cr	119.5	720.0	.....	.....	.....	.....	.....	870	1,300	7
Copper manganese alloys:											
Therlo	Cu-Mn-Al	45.4	280.0	15–30 1×10^{-6}	0.3	8.15	78,400	0.000194	100	.....	1
Manganin	Cu-Mn-Ni	47.8	294.0	3×10^{-6}	5.0	.....	.....	.....	100	.....	1
Tarnac	Cu-Mn-Ni	42.0	249.0	0.000025	.....	.....	.....	.....	.....	.....	2

*1. Driver-Harris Wire Co.
2. The Electrical Alloy Co.
3. Thomas Prosser & Son.
4. Murray Wire Co.
5. Amer. Steel & Wire Co.
6. Herman Boker & Co.
7. General Electric Co.
8. C. Schniewindt.

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cent. At zero deg. cent. it has a resistivity of approximately 60,000 ohm-cm. The dielectric constant ranges from 6.1 to 7.4. It has the peculiar property that its resistivity decreases upon exposure to light; the resistivity in darkness may be anywhere from 5 to 200 times the resistivity under exposure to light. See paper by W. J. Hammer, Trans. A. I. E. E., 1903, Vol. XXI, pp. 372 to 393.

RESISTOR MATERIALS

148. Nickel silver is an alloy of copper, nickel and zinc. It is usually listed commercially in terms of its nickel content; thus 18 per cent. wire contains 18 per cent. of nickel. The properties vary considerably with the composition. Perrine gave the following composition of three grades of nickel silver: 57 Cu, 12.5 Ni, 30.5 Zn; 56 Cu, 20 Ni, 24 Zn; 50 Cu, 30 Ni, 20 Zn. The resistivities were respectively in the ratio 1 : 1.25 : 2.51. Eighteen per cent. alloy has about 18 times the resistivity of copper, and 30 per cent. alloy has about 28 times the resistivity of copper. See Par. **147.**

149. Copper-manganese alloy containing either nickel or aluminum is used for resistors, and has a very low temperature coefficient. The alloy composed of copper, ferro-manganese and nickel, or copper, manganese and nickel, is known as **manganin.** The composition of manganin varies somewhat, one formula being 65 Cu, 30 Fe-Mn, 5 Ni.

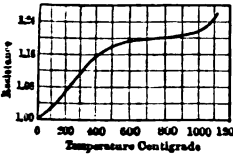


FIG. 13.—Resistance-temperature curve for nichrome.

150. Copper-nickel alloy is used extensively for resistor wires. The alloy of copper and nickel found in nature is known as Monel metal (Par. **399**). See Par. **147.**

151. Ferro-nickel alloy has a very high electrical resistivity but is not as resistant to corrosion, for resistor service, as some other alloys. The nickel-chromium alloys are superior in the respect of having somewhat larger resistivity. See Par. **147.**

152. Nickel-chromium alloy is used for resistor wires where very high resistivity is desired. One alloy of this kind has a resistivity of more than 700 ohms per mil-ft. The nickel-chromium alloy known as "Nichrome" has a characteristic resistance-temperature curve of the form shown in Fig. 13.

CARBON AND GRAPHITE

153. Forms of carbon. Carbon occurs in two forms, amorphous and crystalline. The crystalline forms include **diamond** and **graphite,** the latter also being known as **plumbago.** The amorphous forms include charcoal, coke, lamp black, bone black; coal is an impure variety of amorphous carbon. The density of carbon in the diamond state is 3.47 to 3.56; graphite, 2.10 to 2.32; charcoal, 0.28 to 0.57; coke, 1.0 to 1.7; gas carbon, 1.88; lampblack, 1.7 to 1.8.

154. Resistivity. The resistivity of amorphous carbon (petroleum coke) at ordinary temperature (25 deg. cent.) may be taken as varying between 3,500 and 4,100 microhm-cm. An average value for retort carbon, such as used for electrodes in electric furnaces, at about 3,000 deg. cent., may be taken as 720 microhm-cm. Graphite at 3,000 deg. cent. has a resistivity of approximately 812 microhm-cm. Experiments by Mr. C. A. Hansen* made in the research laboratory of the General Electric Company show that the resistivity of carbon depends upon the temperature at which it is fired. As the temperature of firing increases, the resistivity decreases, approaching a constant value which is approximately the same as that of graphite. If carbon be heated above the temperature at which it was fired, its resistivity is permanently decreased, and upon cooling it will not return to its original value, but to a value corresponding to that which it would have if fired at the temperature to which it has been heated. Also see table of brush characteristics, Par. **155,** and electrode carbon, Par. **159.**

Experiments made by Morris Owen show that graphite possesses magnetic susceptibility, and under certain conditions the electrical resistivity is increased in very marked degree by magnetization.

* *Electrochem. and Met. Ind.*, Vol. VII, p. 514 (1909).

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155. Summary of Brush Characteristics

(National Carbon Co.)

Grade No.	Composition	Resistance (ohms per in. cube)	Transverse strength (lb. per sq. in.)	Hardness (scleroscope)	Carrying capacity (amp. per sq. in. for continuous service on commutating machines)	Maximum peripheral speed (ft. per min.)	Contact drop	Coefficient of friction
543	Metal graphite	0.000003	9,740	4	150	4,000	Very low**	Low
589	Metal graphite	0.000021	8,000	9	150	4,000	Very low**	Low
617	All graphite	0.0015	3,100	33	40	3,500	High	Medium
619	All graphite	0.00075	2,100	15	60	6,000	Low	Low
621	All graphite	0.00012	2,400	12	70	12,000	Very low	Low
628	All graphite	0.0004	4,500	24	60	4,000	Low	Medium
634	All graphite	0.0012	1,100	13	60	12,000	Medium	Low
702	Carbon graphite	0.00105	4,400	31	45	3,500	High	High
808	Graphite and carbon graphite	0.0015	3,200	34	35	3,500	Medium	High
811	Graphite and carbon graphite	0.00070	3,700	36	35	3,000	Very low	High
812	Graphite and carbon graphite	0.0010	5,500	45	45	3,500	Medium	High
833	Graphite and carbon graphite	0.0008	6,000	35	40	4,000	Low	Medium
840	Graphite and carbon graphite	0.0012	3,500	30	45	4,000	Low	Medium

* Much lower than that of carbon.
** Lower than 525.

Also see Whitney, W. R. "Brushes," *Journal Franklin Institute*, 1912; Vol. CLXXIII, pp. 239 to 250.

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156. Resistance of arc lamp carbons. The resistance of ½ in. × 12 in. enclosed arc carbons varies from 0.012 to 0.015 ohms per linear inch. Other sizes down to ¼ in. diameter vary according to their cross-sectional areas. The resistance of a ½-in. diameter projector carbon varies from 0.009 to 0.011 ohms per linear inch. The ½-in. and ⅝-in. carbons vary according to their cross-sectional areas.

All high-grade forms of carbon, such as that used in the manufacture of search-light carbons and also enclosed arc carbons, may be given the value of about 0.002 ohms per cu. in. Flame-arc carbon material such as is used in the homogeneous electrodes varies from 0.004 to 0.006 ohms per cu. in. All the above values are for ordinary room temperatures.

157. Temperature coefficient of resistance. Carbon exhibits a decreasing electrical resistivity and a decreasing thermal resistivity with rising temperature. Graphite exhibits but little change in electrical resistivity, tending downward with rising temperature, but its thermal resistivity increases slightly with rising temperature. The coefficients vary over a considerable range; see Landolt and Bornstein, "Physikalish-Chemische Tabellen," 1912.

158. Resistances of carbon contacts vary with pressure, current and time. See results of investigation published by A. L. Clark in the *Physical Review*, Jan., 1913.

159. Electrode properties of carbon and graphite were given by Hering in his paper, "The Proportioning of Electrodes for Furnaces" (Trans. A. I. E. E., Vol. XXIX, 1910, pp. 485–545), from experimental determinations. The table below is abstracted from Table I in Hering's paper above mentioned; the paper itself gives elaborate details and many curves. Other papers by Hering on this general subject are noted below.* Also see Rasch, Ewald, "Electric Arc Phenomena," published by D. Van Nostrand Co., N. Y., 1913, Chapter III.

Material	Furnace temp. (deg. cent.)	Temp. drop (deg. cent.)	Electrical resistivity, ohm (in-cube)	Thermal conductivity, †watts (in-cube)
Carbon.....	20.0	0.0	0.00181	.....
	360.0	260.0	166	0.95
	751.0	651.0	150	1.32
	942.0	842.0	148	1.38
Graphite.....	20.0	0.0	0.000337	.....
	389.6	289.6	330	3.60
	546.1	446.1	324	3.45
	720.2	620.2	316	3.26
	913.9	813.9	323	3.10

† 1 watt = 0.2389 g-cal. per sec.; 1 g-cal. per sec. = 4.186 watts.

SKIN EFFECT

160. Skin effect is briefly defined in Sec. 2. Also see Sec. 12, Par. **41.**

161. Formulas and tables for skin effect. If R' is the effective resistance of a linear cylindrical conductor to sinusoidal alternating current of given frequency and R is the true resistance with continuous current, then

$$R' = KR \qquad \text{(ohms)} \qquad (13)$$

where K is determined from the table in Par. **165**, in terms of x. The value of x is given by

$$x = 2\pi a \sqrt{\frac{2f\mu}{\rho}} \qquad (14)$$

*"Laws of Electrode Losses in Electric Furnaces;" *Trans.* A. E. S., Vol. XVI, 1909.
"Empirical Laws of Furnace Electrodes;" *Trans.* A. E. S., Vol. XVII, 1910.
"The Design of Furnace Electrodes;" *Electrical World*, June 16, 1910.

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where a is the radius of the conductor in cm., f is the frequency in cycles pe sec., μ is the magnetic permeability of the conductor (here assumed t be constant) and ρ is the resistivity in absohms (10^{-9} ohm) per cm-cube.

If L' is the effective inductance of a linear conductor to sinusoidal alte nating current of a given frequency

$$L' = L_1 + K'L_2 \qquad (1$$

where L_1 is the external portion of the inductance, L_2 is the internal portio (due to the magnetic field within the conductor) and K' is determined fro the table in Par. **165** in terms of x. Thus the total effective inductance pe unit length of conductor is

$$L' = 2 \log_e\left(\frac{d}{a}\right) + K'\left(\frac{\mu}{2}\right) \qquad (10$$

See Sec. 2 for further discussion of inductance of linear conductors; also se Sec. 11. For details underlying the above formulas see Bulletin of th Bureau of Standards, Vol. VIII, No. 1, pp. 172 to 181; 1912. Fig. 14 show values of K in terms of $a\sqrt{f}$ for cylindrical copper conductors of 10 per cent. conductivity. Also see Bureau of Standards Circular No. 7 An integration method of calculating the skin effect is given in Scientifi Paper No. 374, Bureau of Standards, 1920; this paper also shows the increas in skin effect caused by close spacing of parallel conductors.

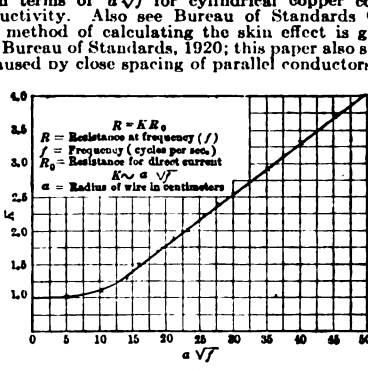


FIG. 14.—Curve showing the proportional change in effective resistance c cylindrical copper conductors with alternating currents.

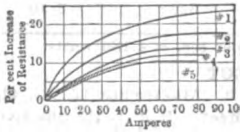


FIG. 15.—Skin effect in copper-clad steel wires at 60 cycles.

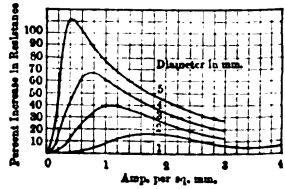


FIG. 16.—Skin effect in iron wires at 50 cycles.

162. Skin effect in copper-clad steel wire is illustrated in Fig. 1 based on tests of the effective resistance of solid round wires at 60 cycl per sec. The effects at 25 cycles are somewhat less. The effects large concentric-lay cables are somewhat greater, and the increase at cycles reaches values as high as from 80 to 100 per cent.; when the core composed of solid copper, the skin effect is less severe. In the small wires (No. 10 to No. 12 A.W.G.) the skin effect at 800 cycles per se with currents of telephonic strength, ranges from 3 to 6 per cent.

163. Skin effect in iron wire at 50 cycles is illustrated in Fig. 16, base on data supplied by the Felten & Guilleaume Carlswerke (Elek. Zeit., De

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10, 1914). In No. 12 B.W.G. iron wire (B. B. grade), at 800 cycles per sec., and with currents of telephonic magnitude, the increase in resistance was found by measurement to be 47 per cent. See Par. **203.**

164. Effect of very high frequencies on iron has been investigated by E. F. W. Alexanderson; see "Magnetic Properties of Iron at Frequencies up to 200,000 Cycles," *Trans.* A. I. E. E., Vol. XXX, 1911, pp. 2433–2454. He concluded that the permeability is unaffected by the frequency. In applying Steinmetz's formula for skin effect (see "Transient Electric Phenomena and Oscillations," New York, 1909), he recommended using average constants as follows: permeability, 2,250 and conductivity, 0.9×10^6, for soft iron.

165. Table of constants for skin-effect formulas (Par. **161**)*

x	K	K'	x	K	K'	x	K	K'
0.0	1.00000	1.00000	4.0	1.67787	0.68632	12.5	4.67993	0.22567
0.1	1.00000	1.00000	4.1	1.71516	0.67135	13.0	4.85631	0.21703
0.2	1.00001	1.00000	4.2	1.75233	0.65677	13.5	5.03272	0.20903
0.3	1.00004	0.99998	4.3	1.78933	0.64262	14.0	5.20915	0.20160
0.4	1.00013	0.99993	4.4	1.82614	0.62890	14.5	5.38560	0.19468
0.5	1.00032	0.99984	4.5	1.86275	0.61563	15.0	5.56208	0.18822
0.6	1.00067	0.99966	4.6	1.89914	0.60281	16.0	5.91509	0.17649
0.7	1.00124	0.99937	4.7	1.93533	0.59044	17.0	6.26817	0.16614
0.8	1.00212	0.99894	4.8	1.97131	0.57852	18.0	6.62129	0.15694
0.9	1.00340	0.99830	4.9	2.00710	0.56703	19.0	6.97446	0.14870
1.0	1.00519	0.99741	5.0	2.04272	0.55597	20.0	7.32767	0.14128
1.1	1.00758	0.99621	5.2	2.11353	0.53506	21.0	7.68091	0.13456
1.2	1.01071	0.99465	5.4	2.18389	0.51566	22.0	8.03418	0.12846
1.3	1.01470	0.99266	5.6	2.25393	0.49764	23.0	8.38748	0.12288
1.4	1.01969	0.99017	5.8	2.32380	0.48086	24.0	8.74079	0.11777
1.5	1.02582	0.98711	6.0	2.39359	0.46521	25.0	9.09412	0.11307
1.6	1.03323	0.98342	6.2	2.46338	0.45056	26.0	9 44748	0.10872
1.7	1.04205	0.97904	6.4	2.53321	0.43682	28.0	10.15422	0.10096
1.8	1.05240	0.97390	6.6	2.60313	0.42389	30.0	10.86101	0.09424
1.9	1.06440	0.96795	6.8	2.67312	0.41171	32.0	11.56785	0.08835
2.0	1.07816	0.96113	7.0	2.74319	0.40021	34.0	12.27471	0.08316
2.1	1.09375	0.95343	7.2	2.81334	0.38933	36.0	12.98160	0.07854
2.2	1.11126	0.94482	7.4	2.88355	0.37902	38 0	13.68852	0.07441
2.3	1.13069	0.93527	7.6	2.95380	0.36923	40 0	14.39545	0.07069
2.4	1.15207	0.92482	7.8	3.02411	0.35992	42.0	15.10240	0.06733
2.5	1.17538	0.91347	8.0	3.09445	0.35107	44.0	15.80936	0.06427
2.6	1.20056	0.90126	8.2	3.16480	0.34263	46.0	16.51634	0.06148
2.7	1.22753	0.88825	8.4	3.23518	0.33460	48.0	17.22333	0.05892
2.8	1.25620	0.87451	8.6	3.30557	0.32692	50.0	17.93032	0.05656
2.9	1.28644	0.86012	8.8	3.37597	0.31958	60.0	21.46541	0.04713
3.0	1.31809	0.84517	9.0	3.44638	0.31257	70.0	25.00063	0.04040
3.1	1.35102	0.82975	9.2	3.51680	0.30585	80.0	28.53593	0.03535
3.2	1.38504	0.81397	9.4	3.58723	0.29941	90.0	32.07127	0.03142
3.3	1.41999	0.79794	9.6	3.65766	0.29324	100.0	35.60666	0.02828
3.4	1.45570	0.78175	9.8	3.72812	0.28731	∞	∞	0
3.5	1.49202	0.76550	10.0	3.79857	0.28162			
3.6	1.52879	0.74929	10.5	3.97477	0.26832			
3.7	1.56587	0.73320	11.0	4.15100	0.25622			
3.8	1.60314	0.71729	11.5	4.32727	0.24516			
3.9	1.64051	0.70165	12.0	4.50358	0.23501			

* See Bureau of Standards Circular No. 74, pp. 309–311, for additional tables.

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166. Skin effect in steel cables at 50 cycles per sec. is shown in Fig. 17, based on test data from the Allgemeine Elektricitäts Gesellschaft (*Elek. Zeit.*, Dec. 10, 1914).

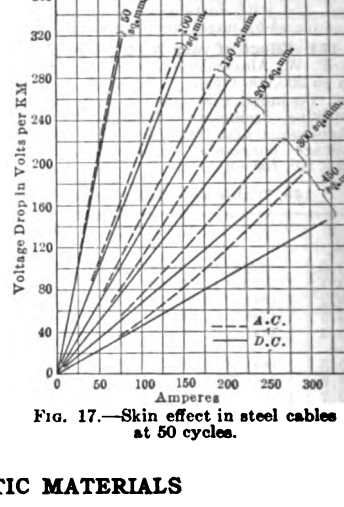


FIG. 17.—Skin effect in steel cables at 50 cycles.

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MAGNETIC MATERIALS

CLASSIFICATION

168. Paramagnetic materials include all those materials in which the intensity of magnetization (Sec. 2) is a positive quantity. The principal paramagnetic materials are iron, nickel, cobalt, and certain of their alloys; also certain non-ferrous alloys, known as the Heusler alloys. The only materials of great industrial importance are iron and its alloys.

169. Diamagnetic materials are those which are less magnetic than ether or air, or in which the intensity of magnetization is negative. There is no known material in which this effect has more than a very feeble intensity. Bismuth is the leading example of materials of this class.

170. Commercial magnetic materials can be classified as follows: cast iron, wrought or puddled iron, soft or low-carbon steel, high-carbon steel, and alloy steel. These are the materials whose properties are important in practical engineering work.

171. Retentive and non-retentive materials. The commercial materials are divisible as a whole into two classes, one suitable for all applications in which the retentivity, coercive force and hysteresis should be as small as possible, the other suitable for applications in which maximum retentivity is the most-desired characteristic. The former class is useful in all types of electromagnetic mechanisms, such as generators, motors, transformers, electromagnets, etc.; the second class is useful only in permanent magnets, measuring instruments, magnetos, relays, etc.

COMPOSITION AND PROPERTIES

172. Dependence of properties upon composition and treatment. The magnetic properties of all materials depend upon the chemical composition, heat treatment and mechanical treatment. These factors are considered in some detail in the succeeding paragraphs.

173. Effect of impurities on magnetic properties of iron. The general effect of impurities is to decrease the permeability and increase the iron loss. Most impurities are as a whole injurious in their effect, but there are certain apparent exceptions. The effect of silicon appears to be to decrease the iron loss and increase the permeability up to inductions from 12,000 to 14,000

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gauss, after which the permeability decreases below that of soft iron, while the iron loss begins to increase rapidly. See also Ruder, W. E., "The Effect of Chemical Composition upon the Magnetic Properties of Steels;" *General Electric Review*, March, 1915, pp. 197 to 203.

174. Effect of carbon. Carbon increases the resistivity, decreases the permeability, lowers the saturation point and increases the coercive force and the retentivity. Concurrently the hysteresis loop is broadened and its area increased. These effects are greater in hardened steel than in soft or annealed material. In slowly cooled iron-carbon alloys the carbon exists as pearlite up to the eutectoid point (about 0.85 carbon); above this point the carbon exists as cementite (Fe_3C). The cementite carbon diminishes the conductivity less than does the pearlite carbon. At a quenching temperature of 850 deg. cent. the limit of dissolved carbon is about 1.4 per cent.; no excess of carbon above 1.4 is soluble at this temperature.

175. Effect of manganese. Very small proportions of manganese are not injurious in any substantial degree, but it is customary to limit the proportion of manganese as much as practicable. The true effect of small proportions of manganese is difficult to determine because of its association in most cases with carbon. See *Jour.* I. E. E., April, 1911, Vol. XLVI, No. 206, pp. 263 to 266. When the manganese content reaches 12 per cent. the steel becomes practically non-magnetic.

176. Effects of silicon and aluminum. The researches of Barrett, Brown and Hadfield (1900 and 1902) established the fact that the only magnetic alloys superior to the purest commercial iron are the alloys of iron with silicon, and with aluminum. The best silicon alloy contained 2.5 per cent. of silicon, and the best aluminum alloy contained 2.25 per cent. of aluminum.

	Maximum permeability	$\mathfrak{G}$ for maximum permeability	Hysteresis loss, ergs per cu. cm. per cycle for $\mathfrak{G}$ (max) = 9,000	Coercive force for $\mathfrak{G}$ (max) = 17.700
Swedish charcoal iron.....	2,100	4,000	2,334	1.10
2.5 per cent. silicon.....	5,000	4,000	1,549	0.80
2.25 per cent. aluminum..	5,400	5,000	1,443	0.80

Guggenheim has shown (Elek. Kraft U. Bahnen, Sept. 24, 1910), for iron containing 0.2 per cent. of carbon, that silicon in quantities up to 1.8 per cent. decreases the permeability, but from 1.8 to 5 per cent. it improves the permeability and decreases the hysteresis loss; for $\mathfrak{G}$(max) = 10,000 in sheets 0.5 mm. thick the hysteresis loss was 2,910 ergs per cu. cm. per cycle, for best silicon steel, compared with 6,000 ergs for ordinary sheet iron.

For electrical and mechanical effects of silicon and aluminum, see appropriate portions of this section.

177. Effect of nickel. The addition of nickel, up to 2 per cent., causes little change in magnetic quality (Burgess and Aston). A higher nickel content rapidly decreases the permeability. At 25 to 30 per cent. nickel, the magnetic properties are greatly impaired, but improve again upon a further increase in nickel.

178. Effects of tungsten, chromium and molybdenum. These elements have the general property of increasing the magnetic hardness and particularly the coercive force, making a very desirable steel for permanent magnets. See "Magnet Steel," Par. 225 to 250.

179. Effects of arsenic and tin. These elements are similar in their effects to silicon and aluminum, increasing the resistivity and reducing the hysteresis loss. Tin increases the permeability at higher inductions and decreases the hysteresis loss even more than silicon.

180. Sulphur, phosphorus and oxygen are in general injurious in their effects, even in small percentages.

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181. Effect of heat treatment. Suitable heat treatment during manufacture reduces the iron loss, increases the permeability and gives better physical properties. The best physical properties and the permeability are to some extent opposed, and the most suitable heat treatment as regards magnetic properties is not generally the one which gives the highest physical properties. The general method of annealing is in boxes, under cover, with slow cooling.

182. Effect of temperature. Both iron and steel lose their magnetic properties at about 750 to 800 deg. cent., and are non-magnetic above that temperature. The exact temperature at which this transformation occurs is somewhat variable, and depends upon the chemical composition of the metal.

183. Effect of temperature on permeability. Hopkinson's experiments (Phil. Mag. and Proc. Roy. Soc.) showed that with weak magnetizing forces the permeability increases with rises of temperature up to the critical point, or about 785 deg. cent., above which iron becomes non-magnetic. Under moderate magnetizing forces the permeability first increases slightly, with rise of temperature, and then decreases rapidly as the critical point is approached. Under strong magnetizing forces the permeability suffers no change at first, and then decreases gradually as the critical point is approached. See Chap. VIII of Ewing's "Magnetic Induction in Iron and Other Metals."

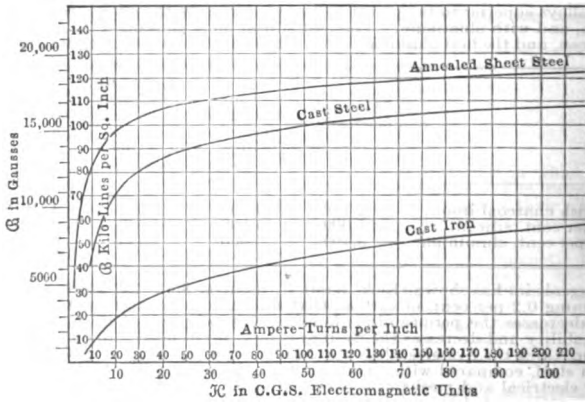


FIG. 18.—Normal saturation curves (General Electric Co.).

184. Normal saturation curves for cast-iron, cast-steel and annealed-steel (low-carbon) sheets, of the qualities ordinarily used in electrical construction, are given in Fig. 18. Also see Fig. 37 (Par. **79**) in Sec. 8; Fig. 33 (Par. **35**) in Sec. 7; and "Commercial Sheets" in this section. For precautions and rules in extrapolating magnetization curves see Ball, J. D., *General Electric Review*, Jan. 1915, pages 31 to 33.

185. Induction-permeability curves for cast iron and malleable iron are given in Fig. 19. These curves are typical of the shape of induction-permeability curves in general.

186. Aging. Aside from the immediate change in the magnetic quality of iron which results from heating, it produces a slow deterioration which results in reduced permeability and increased hysteresis. Even so low a temperature as 50 deg. cent., if continued for some weeks, will produce an appreciable effect. The tests by S. R. Roget (*Proc.* Roy. Soc., May 12, 1898 and Dec. 8, 1898) showed that the hysteresis loss increased 9 per cent. when the iron was

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heated for 27 days at 50 deg. cent.; 53 per cent. when heated for 25 days at 65 deg. cent.; 89 per cent. when heated for 25 days at 87 deg. cent.; 140 per cent. when heated for 25 days at 135 deg. cent. Also see Mordey, W. M., Proc. Roy. Soc., June, 1895; also see aging tests in "Electric Machine Design," by Parshall and Hobart; Allen, T. S., "The Comparative Aging of Electric Sheet Steels;" *Electrical World*, 1908, Vol. LII, p. 579.

187. **Non-aging steel.** Silicon-steel, aside from having low hysteresis and high resistivity, also possesses the valuable property of being non-aging. That is to say, its magnetic properties are not impaired by prolonged heating at moderate temperatures, but on the contrary may be slightly improved. While as much as 3 to 4 per cent. of silicon is present in silicon-steel, it is also useful, in much smaller quantities, in improving the aging qualities of low-carbon steel. Parshall and Hobart recommend ("Electric Machine Design," p. 36) the following composition for sheet steel having good aging qualities: carbon, 0.06; manganese, 0.50; silicon, 0.01; sulphur, 0.03; phosphorus, 0.08.

188. **Effects of mechanical stress on magnetization.** Ewing states (Chap. IX, "Magnetic Induction in Iron and Other Metals") that the presence of any moderate amount of longitudinal pull increases the susceptibility when the magnetism is weak, but reduces it when the magnetism is strong. With hardened metal the effects of stress are in general much greater than with annealed metal.

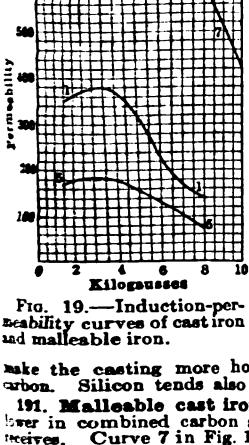


FIG. 19.—Induction-permeability curves of cast iron and malleable iron.

189. **Page effect** is the faint metallic sound resembling a light blow which is heard when a piece of iron is suddenly magnetized or demagnetized.

190. **Cast iron** is magnetically inferior to wrought iron or low steel, but is used to a limited extent on account of the facility with which it can be molded into complex forms. The permeability is decreased by the presence of carbon, the effect being in the ratio of combined to graphitic carbon. Cast iron of good magnetic quality contains from 3 to 4.5 per cent. carbon, of which from 0.2 to 0.8 per cent. is in the combined form. A normal induction curve for cast iron is given in Fig. 18. Curve 1 in Fig. 19 applies to cast iron containing 0.195 combined carbon, 3.29 graphitic carbon, 2.01 silicon, 0.320 manganese, 0.988 phosphorus and 0.08 sulphur. Curve 5 is for cast iron containing 0.72 combined carbon, 2.07 silicon, 0.38 manganese, 0.85 phosphorus and 0.035 sulphur.

Silicon and aluminum in small proportions make the casting more homogeneous and tend to reduce the combined carbon. Silicon tends also to counteract sulphur.

191. **Malleable cast iron** is magnetically superior to cast iron, being lower in combined carbon and improved by the heat treatment which it receives. Curve 7 in Fig. 19 is for malleable cast iron (see Parshall and Hobart, "Electric Machine Design") containing 0.83 combined carbon, 1.201 graphitic carbon, 0.93 silicon, 0.116 manganese, 0.039 phosphorus and 0.060 sulphur.

192. **Wrought iron** is among the best of magnetic materials from the standpoint of permeability, but has higher core losses than silicon steel. See Par. 200 comparing Swedish iron with other materials.

193. **Rolled steel** of the low-carbon variety is used very extensively in the form of electrical sheets and rods. A normal induction curve is shown in Fig. 18. Commercial sheets are described in Par. 217 to 224.

194. **Cast steel** is extensively used for those portions of magnetic circuits which carry uniform or continuous flux and need superior mechanical strength. Parshall and Hobart state ("Electric Machine Design," p. 22) that cast steel of good magnetic qualities should be limited in its composition as follows: combined carbon, 0.25; silicon, 0.20; manganese, 0.50; phos-

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phorus, 0.08; sulphur, 0.05. A normal induction curve is shown in Fig. 18.

195. Alloy steel. The principal alloy steel in extensive use is silicon steel. Its properties are covered under "Commercial Sheets," Par. **217** to **224**, and Figs. 24 and 26. It is low in core loss, non-aging, and high in permeability except at the higher densities. Tungsten steel and tungsten-chrome steel are used extensively for permanent magnets; see "Magnet Steel," Par. **225** to **230**. **Mitis iron** is steel to which has been added a small proportion of aluminum, ranging from 0.06 to 0.27 per cent. Magnetically it is a little better than ordinary steel up to densities of about 100 kilolines per sq. in., and inferior at higher densities. See Parshall and Hobart, "Electric Machine Design;" published by *Engineering*, London, 1906; p. 26. This material is now seldom used.

196. Best composition of dynamo sheets; De Nolly and Veyret. High carbon and cold working are both injurious to electrical sheets. The recommended composition and treatment is as follows: (1) The steel should have less than 0.1 per cent. carbon, from 3 to 4 per cent. silicon, less than 0.3 per cent. manganese, less than 0.03 per cent. sulphur and phosphorus; (2) the sheets after rolling should be annealed at 750 to 800 deg. cent. with slow cooling; (3) the rolling should be finished at low temperature; (4) after final annealing, no cold working should be allowed (IX 5, No. 9, Sixth Congress of Int. Assoc. for Testing Materials, New York City, 1912).

197. Electrolytic iron melted in vacuo. "Magnetic and Other Properties of Electrolytic Iron Melted in Vacuo" is the subject of a valuable monograph by T. D. Yensen, and is published as Bulletin No. 72, Engineering Experiment Station, Univ. of Ill., 1914; this monograph is the source of the following data.

The electrolytic iron was doubly refined from Swedish charcoal iron anodes, and contained from 99.97 to 99.98 per cent. of chemically pure iron, 0.006 carbon and 0.01 silicon. The iron as deposited was crushed, cleaned and placed in a magnesia crucible; then it was melted in a vacuum furnace and allowed to cool. Finally it was hot forged to rods about 0.5 in. diameter and 20 in. long. The average results from rods annealed at 900 deg. cent. were as follows:

Carbon content, per cent	0.0125
Maximum permeability	12,950
Flux density at maximum permeability	6,550
Hysteresis loss, ergs per cu. cm. per cycle:	
At $\mathfrak{B}$ (maximum) = 10,000	1,060
At $\mathfrak{B}$ (maximum) = 15,000	1,990
Coercive force, $\mathfrak{B}$ (maximum) = 15,000	0.34
Retentivity, $\mathfrak{B}$ (maximum) = 15,000	9,940
Resistivity (microhm-cm.) at 20 deg. cent.	9.96
Critical temp., deg. cent.	894

The magnetic quality of electrolytic iron melted *in vacuo* is decidedly superior to any grade of iron thus far produced; the maximum permeability obtained was 19,000 at a density of 9,500 gausses, and the average hysteresis loss obtained is less than one-half that found in the best grades of commercial transformer iron. Swedish charcoal iron melted *in vacuo* approaches electrolytic iron in magnetic quality, due chiefly to reduction of carbon content. Low-carbon iron melted *in vacuo* will lose 50 to 90 per cent of its original carbon. Electrolytic iron is at present purely a laboratory or experimental product, and therefore too expensive for commercial applications. See the bibliography appended to Mr. Yensen's monograph. Also see *Proc.* A. I. E. E., Feb., 1915, pp. 237–261.

198. Approximate saturation values of different magnetic materials are given by Steinmetz as follows, in gausses.

Iron	20,000	Magnetite	5,000
Cobalt	12,000	Manganese alloys up to	4,000
Nickel	6,000		

199. Maximum saturation intensity. Hadfield and Hopkinson have shown that a great number of magnetic materials, including commercially pure iron and many iron alloys, have a definite saturation intensity

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magnetism (Hadfield, Sir R. A. and Hopkinson, B., "The Magnetic Properties of Iron and Its Alloys in Intense Fields," *Jour.* I. E. E., April, 1910, Vol. XLVI, pp. 235–306). The intensity of magnetisation is defined as the quantity J in the formula $\mathfrak{B} = \mathfrak{H} + 4\pi J$, or the magnetic moment per unit of volume.

Every alloy which they examined was found to have a definite saturation intensity of magnetism, which they termed the **specific magnetism.** This intensity was reached in most cases in a field of 5,000 units. The specific magnetism of commercially pure iron of density 7.80 was found to be 1,680 within 1 per cent. The presence of carbon in annealed iron-carbon steel reduces the specific magnetism by a percentage equal to six times the percentage of carbon, if other elements are present only in small proportions. No alloy was noted having a higher specific magnetism than pure iron. Quenching an iron-carbon alloy from a high temperature reduces its specific magnetism by a large but uncertain amount. The addition of silicon or aluminum to iron reduces the specific magnetism roughly in proportion to the amount added; but if carbon is present, silicon seems to neutralise it to some extent.

200. Comparisons of magnetic materials

(T. D. Yensen, Bulletin No. 72, Eng. Exp. Sta., Univ. of Ill., 1914)

Material	Carbon content (per cent.)	Max. permeability	Flux density for max. permeability	Hysteresis loss in ergs per cu. cm. per cycle		Coercive force for $\mathfrak{B}$ (max.) = 15,000	Retentivity for $\mathfrak{B}$ (max.) = 16,000	Resistivity at 20 deg. cent. (microhm-cm.)
				$\mathfrak{B}$ (max.) = 10,000	$\mathfrak{B}$ (max.) = 15,000			
Swedish charcoal iron cut from plate.	0.163	4,870	6,600	2,490	4,530	0.95	8,000	10.57
Standard transformer steel.	.....	3,850	7,000	3,320	5,910	1.33	9,900	11.09
Four per cent. silicon steel.	.....	3,400	4,300	2,260	3,030	0.88	5,400	51.15
Swedish charcoal iron remelted *in vacuo*.	0.008	10,350	7,000	1,290	2,640	0.48	11,200	10.30
Electrolytic iron melted *in vacuo*.	0.0125	12,950	6,550	1,060	1,990	0.34	9,940	9.96

201. Formula for induction-permeability curve. A. S. McAllister has shown that the induction-permeability curve can be expressed with a fair degree of accuracy by an equation of the form

$$\mu = 2{,}800 - 3.2\left[\frac{(7{,}500 - \mathfrak{B})^2}{10^4}\right] \qquad (17)$$

The constants in this equation hold for the ordinary grades of sheet iron, between the limits $\mathfrak{B} = 0$ and $\mathfrak{B} = 15{,}000$, where $\mathfrak{B}$ is the maximum instantaneous value. The numerical constants take different values for cast iron, cast steel, silicon steel, etc. See McAllister, "Alternating-current Motors," New York, 1909, p. 137.

202. Permeability in weak fields. Ewing gives the permeability in very weak fields, with values of $\mathfrak{H}$ less than unity, according to the following formula based on investigations by Baur.

$$\mu = 183 + 1{,}382\mathfrak{H} \qquad (18)$$

This applies to soft iron. Lord Rayleigh found for harder grades of iron,

$$\mu = 81 + 64\mathfrak{H} \qquad (19)$$

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The latter applies to hard-drawn iron wire; in another case the initia permeability was 87. The foregoing relationships are accounted for by th fact that the saturation curve is sensibly a parabola in its earliest stage starting, however, with a finite inclination to the axis of $\mathfrak{H}$. For ex tremely feeble forces it is virtually an inclined straight line. See Ewing, J A., "Magnetic Induction in Iron and Other Metals," London, 1900, 3rd rev d., Chap. VI.

203. Permeability of iron at high frequencies has been investigate by E. F. W. Alexanderson and H. Pender (see "Magnetic Properties of Iro at Frequencies up to 200,000 Cycles," Trans. A. I. E. E., 1911, Vol. XXX pp. 2433–2454). Mr. Alexanderson concluded that iron has practically th same permeability at 200,000 cycles as at 60 cycles, but the magnetic pene tration is greatly reduced at high frequencies, on account of the excessive ski effect, which must be taken into full account. See Par. **164.**

204. Heusler's alloys are composed of copper, manganese and aluminum and possess marked magnetic properties. The permeability increases wit the addition of manganese until the proportions of manganese and aluminur are the same relatively as their atomic weights (Par. **432**). The maximur magnetization obtained is about one-third of that of the best iron.* Copp serves apparently no other purpose than to make the alloy soft enough t be cast and handled, McTaggart* performed experiments on these alloy varying the composition in many ways. The particular composition whic exhibited the best magnetic properties contained 14.3 per cent. aluminun 28.6 manganese and 57.1 per cent. copper.

Dr. Heusler, who discovered these alloys in 1901, stated that the mo magnetic alloy contained 25 per cent. of manganese, 12.5 per cent. of al minum, and 62.5 per cent. of copper, or in the respective proportions of the atomic weights. Also see tests made by Guthe and Austin, Bulletin of th Bureau of Standards, 1906, Vol. II, No. 2, and tests by Stephenson, Bulleti No. 47, Eng. Exp. Sta., Univ. of Ill., 1910.

205. Electron theory of magnetism. Mr. E. H. Williams has writte an extended monograph on this subject, which is published as Bulleti No. 62, Univ. of Ill., Eng. Exp. Sta., 1912, and contains a bibliograph of the important works up to that date. Also see Chap. XI of Ewing "Magnetic Induction in Iron and Other Metals."

CORE LOSSES

206. Total core loss is composed of two elements, **hysteresis** and eddy currents. These two losses follow different laws, briefly set forth in Sec. 2 The loss may be stated in terms of total energy per unit volume per cycl or it may be stated in terms of power loss per unit weight of material s some stated frequency. The effect of wave-form is discussed in Par. **21** and **211.**

207. Values of hysteresis coefficient for different materials
(M. G. Lloyd)

Material	η	Authority	Material	η	Author-rity
Hard tungsten steel.	0.058	Steinmetz	Soft machine steel.	0.009	Foster
			Annealed cast steel	0.008	Foster
Hard nickel.....	0.039	Steinmetz	No. 36 iron wire...	0.005	Lloyd
Hard cast steel...	0.025	Steinmetz	Ordinary sheet iron	0.004	Lloyd
Magnetic iron ore.	0.020	Steinmetz	Pure iron.....	0.003	Gumlic
Forged steel.....	0.020	Steinmetz	Heusler alloy II...	0.0024	Gumlic
Two-mil steel wire	0.016	Lloyd	Soft iron wire.....	0.002	Foster
Cast iron.....	0.013	Steinmetz	Annealed iron sheet	0.002	Lloyd
Soft nickel.....	0.013	Steinmetz	Ingot iron.....	0.0016	Lloyd
Cast steel.....	0.012	Steinmetz	Best annealed sheet	0.0010	Lloyd
Cobalt.....	0.012	Steinmetz	Silicon steel sheet..	0.0010	Lloyd
Heusler alloy I...	0.012	Gumlich	Silicon steel.....	0.0009	Gumlic
Electrolytic iron..	0.009	Schild	Best silicon steel...	0.0006	Lloyd

See Lloyd, M. G., "Magnetic Hysteresis," *Journal of the Franklin Institut* July, 1910, pp. 1–25.

* McTaggart, H. A. Univ. Toronto Studies, Papers from Phys. Lab., 190 No. 23.

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208. Hysteresis coefficients in Steinmetz's formula $W_h = \eta f B^{1.6}$ are given in Par. **207** (Lloyd, M. G., "Magnetic Hysteresis," Journal of the Franklin Institute, July, 1910, pp. 1–25). In this formula W_h is the loss in ergs per cu. cm. per sec., f is the frequency in cycles per sec., $\mathfrak{B}$ is the maximum induction and is here 10,000 gausses, and η is the hysteresis coefficient. The exponent of $\mathfrak{B}$, which is 1.6, departs widely from this value at very low and very high densities.

209. Total core losses for sheets are given in Fig. 29. Lloyd and Fisher give the following total core losses, in watts per lb. at 60 cycles and 10,000 gausses, for No. 29 gage (3.57 mm.): unannealed, 3.18 to 4.76; annealed, 1.25 to 2.36; silicon steel, 0.665 to 1.06. See *Trans.* A. I. E. E., 1909, Vol. XXVIII, p. 465. Also see Sec. 7, Par. **214**.

210. Effect of wave form upon hysteresis loss. Dr. M. G. Lloyd, in his paper entitled "Dependence of Magnetic Hysteresis upon Wave Form" (Bulletin of the Bureau of Standards, Vol. V, No. 3, Feb. 1909, pp. 381–411), reached the following conclusions.

"For a definite maximum value of the flux density, the hysteresis is greater with a flat wave of flux, but the effect is small, and from the industrial standpoint negligible, even with very distorted waves. If, however, the wave of flux is dimpled, the hysteresis may be much increased.

"The hysteresis determined by the ballistic method may be smaller than that which obtains with the use of alternating current, but the differences are small.

"The separation of hysteresis and eddy-current losses by means of runs at two frequencies, using the Steinmetz formula, is not accurate, but is a close approximation when the sheets are thin."

211. Effect of form-factor upon the iron loss was investigated by Dr. M. G. Lloyd (see "Effect of Wave Form upon the Iron Losses in Transformers," Bulletin of the Bureau of Standards, Vol. IV, No. 4, 1907; also Reprint No. 88), who reached the following conclusions.

"With a given effective electromotive force the iron losses in a transformer depend upon the form-factor of the e.m.f., and vary inversely with it. By proper design of the generator supplying transformers, the iron losses may be reduced to a minimum."

212. Effect of unsymmetrical periodic cycles on hysteresis loss. Mr. M. Rosenbaum in a paper entitled "Hysteresis Loss in Iron, Taken Through Unsymmetrical Cycles of Constant Amplitude," before the I. E. E. (see *Jour.* I. E. E., Mar., 1912), presented the following conclusions.

"It is seen that the hysteresis loss increases very appreciably as direct-current magnetization is superposed on the alternating flux. This phenomenon manifests itself in practice in inductor alternators and static balancers. In some kinds of inductor alternators the flux does not reverse, but oscillates between positive maximum and positive minimum values, thus the iron loss per cu. cm. is much greater in inductor alternators than in the ordinary type for the same change of flux in the armature coil. In static balancers this effect also takes place where the direct-current magnetization is not neutralized. It is therefore important, if high efficiency be aimed at, to neutralize the direct-current flux."

SHEET GAGES

213. Two systems of gaging sheets are in use, the U. S. Standard Gage and the Decimal Gage. These two gages are fully covered in the two succeeding paragraphs. Also see Par. **30**.

214. An act establishing a standard gage for sheet and plate iron and steel. *Be it enacted by the Senate and House of Representatives of the United States of America in Congress assembled,* That for the purpose of securing uniformity, the following is established as the only standard gage for sheet and plate iron and steel in the United States of America, namely: (See Par. **215**.) And on and after July 1, 1893, the same and no other shall be used in determining duties and taxes levied by the United States of America on sheet and plate iron and steel. But this act shall not be construed to increase duties upon any articles which may be imported.

Sec. 2. That the Secretary of the Treasury is authorized and required to prepare suitable standards in accordance herewith.

Sec. 3. That in the practical use and application of the standard gage hereby established a variation of 2.5 per cent. either way may be allowed.

Approved, March 3, 1893.

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215. U. S. standard sheet gage

Number of gage	Approximate thickness in fractions of an inch	Approximate thickness in decimal parts of an inch	Approximate thickness in millimeters	Weight per square foot in ounces avoirdupois	Weight per square foot in pounds avoirdupois	Weight per square foot in kilograms	Weight per square meter in kilograms
0000000	1–2	0.5	12.7	320	20.0(0)	9.0(72)	97.(65)
000000	15–32	0.46(875)	11.9(0625)	300	18.7(5)	8.5(05)	91.(55)
00000	7–16	0.43(75)	11.1(125)	280	17.5(0)	7.9(83)	85.(44)
0000	13–32	0.40(625)	10.3(1875)	260	16.2(5)	7.3(71)	79.(33)
000	3–8	0.375	9.5(25)	240	15.0	6.8(04)	73.(24)
00	11–32	0.343(75)	8.7(3125)	220	13.7(5)	6.2(37)	67.(13)
0	5–16	0.312(5)	7.9(375)	200	12.5(0)	5.6(7)	61.(03)
1	9–32	0.281(25)	7.1(4375)	180	11.2(5)	5.1(03)	54.(93)
2	17–64	0.265(625)	6.7(46875)	170	10.6(25)	4.8(19)	51.(88)
3	1–4	0.25	6.3(5)	160	10.0	4.5(36)	48.(82)
4	15–64	0.234(375)	5.9(53125)	150	9.3(75)	4.2(52)	45.(77)
5	7–32	0.218(75)	5.5(5625)	140	8.7(5)	3.96(9)	42.(72)
6	13–64	0.203(125)	5.1(59375)	130	8.1(25)	3.68(5)	39.6(7)
7	3–16	0.187(5)	4.7(625)	120	7.5	3.40(2)	36.6(2)
8	11–64	0.171(875)	4.3(65625)	110	6.8(75)	3.11(8)	33.5(7)
9	5–32	0.156(25)	3.96(875)	100	6.2(5)	2.83(5)	30.5(2)
10	9–64	0.140(625)	3.57(1875)	90	5.6(25)	2.55(2)	27.4(6)
11	1–8	0.125	3.17(5)	80	5.0	2.26(8)	24.4(1)
12	7–64	0.109(375)	2.77(8125)	70	4.3(75)	1.98(4)	21.3(6)
13	3–32	0.093(75)	2.38(125)	60	3.75	1.70(1)	18.3(1)
14	5–64	0.078(125)	1.98(4375)	50	3.12(5)	1.41(7)	15.2(6)
15	9–128	0.070(8125)	1.78(59375)	45	2.81(25)	1.27(6)	13.7(3)
16	1–16	0.062(5)	1.58(75)	40	2.5	1.13(4)	12.2(1)
17	9–160	0.056(25)	1.42(875)	36	2.25	1.02(1)	10.9(9)
18	1–20	0.05	1.27	32	2.0	0.90(72)	9.7(65)

NOTE.—Numbers within parentheses represent higher precision than the tolerance limit of plus or minus 2.5 per cent.

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215. U. S. standard sheet gage.—*Continued*

Number of gage	Approximate thickness in fractions of an inch	Approximate thickness in decimal parts of an inch	Approximate thickness in millimeters	Weight per square foot in ounces avoirdupois	Weight per square foot in pounds avoirdupois	Weight per square foot in kilograms	Weight per square meter in kilograms
19	7–160	0.043(75)	1.11(125)	28	1.75	0.79(88)	8.5(44)
20	3–80	0.0375	0.95(25)	24	1.50	0.68(04)	7.3(24)
21	11–320	0.0343(75)	0.87(3125)	22	1.37(5)	0.62(37)	6.7(13)
22	1–32	0.0312(5)	0.79(3750)	20	1.25	0.56(7)	6.1(03)
23	9–320	0.0281(25)	0.71(4375)	18	1.12(5)	0.51(03)	5.4(93)
24	1–40	0.025	0.63(5)	16	1.0	0.45(36)	4.8(82)
25	7–320	0.0218(75)	0.55(5625)	14	0.87(5)	0.396(9)	4.2(72)
26	3–160	0.0187(5)	0.47(625)	12	0.75	0.340(2)	3.66(2)
27	11–640	0.0171(875)	0.43(65625)	11	0.68(75)	0.311(9)	3.35(7)
28	1–64	0.0156(25)	0.396(875)	10	0.62(5)	0.283(5)	3.05(2)
29	9–640	0.0140(625)	0.357(1875)	9	0.56(25)	0.255(1)	2.74(6)
30	1–80	0.0125	0.317(5)	8	0.5	0.226(8)	2.44(1)
31	7–640	0.0109(375)	0.277(8125)	7	0.43(75)	0.198(4)	2.13(6)
32	13–1280	0.0101(5625)	0.257(96875)	6½	0.40(625)	0.184(3)	1.98(3)
33	3–320	0.0093(75)	0.238(125)	6	0.375	0.170(1)	1.83(1)
34	11–1280	0.0085(9375)	0.218(28125)	5½	0.343(75)	0.155(9)	1.67(8)
35	5–640	0.0078(125)	0.198(4375)	5	0.312(5)	0.141(7)	1.52(6)
36	9–1280	0.0070(3125)	0.178(59375)	4½	0.281(25)	0.127(6)	1.37(3)
37	17–2560	0.0066(40625)	0.168(671875)	4¼	0.265(625)	0.120(5)	1.29(7)
38	1–160	0.0062(5)	0.158(75)	4	0.25	0.113(4)	1.22(1)

NOTE.—Numbers within parentheses represent higher precision than the tolerance limit of plus or minus 2.5 per cent.

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216. Standard decimal gage for sheet iron and steel adopted by the Assoc. of Amer. Steel Manufacturers and the Amer. Railway Master Mechanics Assoc. is based on the following standard thicknesses, expressed in in.

0.002	0.012	0.022	0.040	0.065	0.090	0.135	0.220
0.004	0.014	0.025	0.045	0.070	0.095	0.150	0.240
0.006	0.016	0.028	0.050	0.075	0.100	0.165	0.250
0.008	0.018	0.032	0.055	0.080	0.110	0.180	.....
0.010	0.020	0.036	0.060	0.085	0.125	0.200	.....

The decimal system, denoting the thickness in thousandths of an inch, was endorsed by the A. S. M. E. Committee on Standard Thickness Gage for Metals. The weights are usually calculated on the basis of 480 lb. per cu. ft. for iron and 490 lb. for steel.

COMMERCIAL SHEETS

217. Electrical sheets is the trade term for iron and steel sheets used in the manufacture of punchings for laminated cores or magnetic circuits.

218. Grades. There are several grades of commercial sheets, suited to different classes of electrical apparatus and graded according to total core losses under similar conditions of service. See Par. **219**.

219. Data on American Sheet and Tin Plate Company's commercial sheets

	"American armature" sheets	"U. S. electrical" sheets	"Apollo special Electrical" sheets
Grade of steel (open hearth)	Soft	Soft	4% silicon
Specific gravity, in sheets	7.79	7.72	7.5
Tensile strength, parallel to grain	48,000	52,000	96,000
Yield point, parallel to grain	30,000	35,000	29,000
Elong. in 8 in., parallel to grain	21%	25%	2.4%
Tensile strength, transverse to grain	55,000	61,000	102,000
Yield point, transverse to grain	33,000	38,000	22,000
Elong. in 8 in., transverse to grain	22%	19%	2.1%
Resistivity, microhm-cm	8 to 12	15 to 18	40 to 50
Hysteresis loss at $\mathfrak{B} = 10{,}000$ in ergs per cu. cm. per cycle.	4042	3336	1796
Hysteresis coefficient	0.001609	0.001328	0.000715

The tensile tests given above represent only a few tests and consequently are not average results.

"Apollo Special Electrical" sheets are composed of silicon steel alloy containing about 4 per cent. of silicon. They are non-aging and specially suited for transformer cores.

"Extra Apollo Special Electrical" sheets are selected stock from the above grade and are especially suitable for the highest efficiency transformers.

"Dynamo Special Electrical" sheets are composed of silicon steel alloy containing about 3 per cent. of silicon. The density is about 7.55 and the resistivity is approximately 40 microhm-cm. They are free from brittleness and are non-aging. The usual application of this grade is to transformer cores and stators of induction motors.

"U. S. Electrical" sheets are composed of medium silicon steel alloy. They are practically non-aging and are applicable to dynamo and motor work.

"American Armature" sheets are composed of a low silicon steel alloy which is slightly aging, but suitable for motor work where the lowest core loss is not essential, especially for laminated fields.

Curves of average induction, permeability and hysteresis in these three grades are given in Figs. 20 to 25.

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220. Maximum total losses of electrical sheets

Total losses at 10,000 gausses; as determined under American Society for Testing Materials Specification "A34-14"

(American Sheet & Tin Plate Co.)

	30 G.	29 G.	28 G.	27 G.	26 G.	25 G.	24 G.
Apollo Special Electrical (non-aging, density 7.50)							
Watts per pound, 60 cycles	0.86	0.86	0.89	0.94	0.98	1.04	1.10
Watts per kilogram, 60 cycles	1.90	1.90	1.96	2.07	2.16	2.29	2.42
Watts per pound, 50 cycles	0.71	0.71	0.73	0.77	0.80	0.85	0.90
Watts per kilogram, 50 cycles	1.57	1.57	1.61	1.70	1.76	1.87	1.98
Extra Apollo Special Electrical (non-aging, density 7.50)							
Watts per pound, 60 cycles	....	0.80	....	....	....	....	....
Watts per kilogram, 60 cycles	....	1.75	....	....	....	....	....
Watts per pound, 50 cycles	....	0.66	....	....	....	....	....
Watts per kilogram, 50 cycles	....	1.45	....	....	....	....	....
Dynamo Special Electrical (non-aging, density 7.50)							
Watts per pound, 60 cycles	0.95	0.97	1.01	1.04	1.08	1.13	1.17
Watts per kilogram, 60 cycles	2.10	2.14	2.22	2.29	2.38	2.49	2.57
Watts per pound, 50 cycles	0.78	0.80	0.83	0.86	0.89	0.93	0.96
Watts per kilogram, 50 cycles	1.72	1.76	1.83	1.90	1.96	2.05	2.12
U. S. Electrical (practically non-aging, density 7.70)							
Watts per pound, 60 cycles	1.38	1.45	1.52	1.62	1.68	1.82	2.05
Watts per kilogram, 60 cycles	3.04	3.19	3.35	3.56	3.70	4.00	4.51
Watts per pound, 50 cycles	1.13	1.18	1.24	1.30	1.36	1.50	1.65
Watts per kilogram, 50 cycles	2.49	2.60	2.73	2.86	3.00	2.30	3.63
American Armature (slight aging, density 7.70)							
Watts per pound, 60 cycles	1.65	1.75	1.95	2.05	2.19	2.50	2.80
Watts per kilogram, 60 cycles	3.63	3.85	4.29	3.51	4.82	5.50	6.16
Watts per pound, 50 cycles	1.32	1.40	1.56	1.64	1.76	2.00	2.24
Watts per kilogram, 50 cycles	2.90	3.08	3.43	3.61	3.87	4.40	4.93

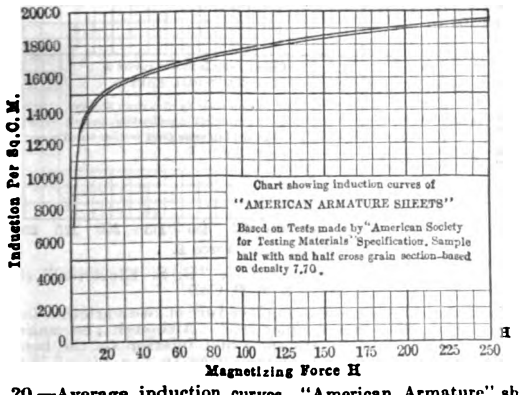


FIG. 20.—Average induction curves, "American Armature" sheets. (A. S. & T. P. Co.).

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221. Effect of mechanical working on sheets. The only working the material receives is punching and compression in the finished core. The effect of punching is to deteriorate the magnetic properties, which can be removed by subsequent annealing, but if the cutting edges are sharp the effect is very small.

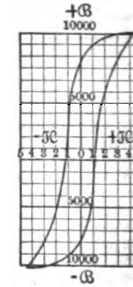


FIG. 21.—Average hysteresis loop, "American Armature" sheets. (A. S. & T. P. Co.).

222. Data on Follansbee steel sheets are given in Figs. 26 to 28. Normal induction curves are shown in Fig. 26. Curves of total core loss are given in Figs. 27 and 28, all data being supplied by Follansbee Brothers Company. Both grades, carbon steel and silicon steel, are made by the basic open-hearth process. Further data may be obtained from articles by J. G. Homan in the *Electrical World*, Sept. 7, 1912, pp. 501–502, and the *Iron Age*, Jan. 2, 1913.

223. Stalloy is the trade name for a commercial transformer steel. Hamlen and Rossiter (*Electrician* (London), Nov. 3, 1911) found the maximum permeability to be as follows: unannealed, 3,100 at $\mathfrak{B} = 4{,}500$; annealed, 4,200 at $\mathfrak{B} = 7{,}000$. Hysteresis loss, 2,500 ergs per cu. cm. per cycle at $\mathfrak{B} = 10{,}000$.

224. Curves of total core losses in electrical sheets are given in Fig. 29, taken from the article on "Transformers," by Dr. A. S. McAllister in the 3rd edition of the Standard Handbook.

MAGNET STEEL

225. Desired characteristics in permanent magnets are maximum retentivity or retained flux, high coercive force and permanency or non-aging characteristics. Alloy magnet steels having a coercive force of 60 to 70 units have in recent years replaced the plain carbon steels, whose coercive force cannot be made to exceed 45 to 50 units.

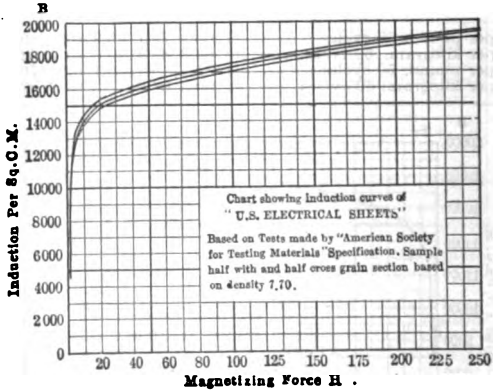


FIG. 22.—Average induction curves, "U. S. Electrical" sheets (A. S. & T. P. Co.).

226. Magnet steels at present employed are of two varieties, *i.e.*, tungsten magnet steel and chromium magnet steel. Although the magnetic properties of the chrome variety are somewhat inferior to the best tungsten steels, the former have come into use owing to the recent high price of tungsten and the scarcity of supply. In terms of the average properties of tungsten magnet steel, the residual flux (retentivity) of chrome magnet steel averages about 88 per cent. and the coercive force averages about 96 per cent.

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227. **Carbon magnet steel** is a high-carbon steel, and must be hardened by quenching after it has been forged and machined to shape. Fig. 30 shows the normal saturation curve and the hysteresis loop of a glass-hard pianoforte steel wire (Ewing, J. A. "Magnetic Induction in Iron and Other Metals." London, 1900; 3rd rev. ed., pp. 83, 84). The maximum permeability in Fig. 30 is only 118. For information relative to the effect of

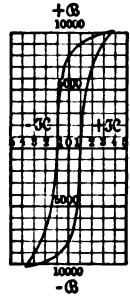


Fig. 23.—Average hysteresis loop, "U. S. Electrical" sheets (A. S. & T. P. Co.).

different degrees of temper on the retentiveness see Bulletin No. 14, by Barus and Stronhal, U. S. Geological Survey, 1885.

Extensive experiments by G. Mars (*Stahl und Eisen*, 1909, Vol. XXIX, p. 1769) indicate that retentivity is a function of the hardness and composition of the metal. Fig. 31 shows relations between carbon content, hardness and

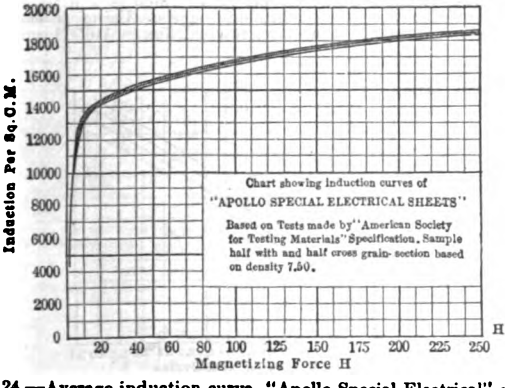


Fig. 24.—Average induction curve, "Apollo Special Electrical" sheets (A. S. & T. P. Co.).

retentivity of carbon steel. The hardness tests were made with a 10-mm. Brinnell ball and a pressure of 3,000 kg. The retentivity increases with the carbon content and hardness up to a point where further increase in carbon is not accompanied by increase in hardness, then the retentivity decreases due to displacement of effective iron by the carbon. Similar experiments with various alloy steels give results shown in Par. 230.

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228. Tungsten magnet steel usually contains from 5 to 6 per cent. of tungsten; and from 0.2 to 0.4 per cent. of chromium, which renders the magnetic properties appreciably better than when this element is entirely omitted, for the reason, it is thought, that the latter element increases the solubility of the tungsten in the molten steel. Quenching is done in running water, from temperatures ranging between 1,550 to 1,600 deg. fahr., depending upon the cross section of the sample. The carbon content in American steels averages about 0.7 per cent., which is a little lower than the average used in the case of chromium steels. Using H max. of 300 gausses, common magnetic values are, residual flux = 10,500, and coercive force = 65.

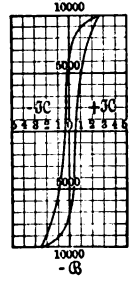


FIG. 25.—Average hysteresis loop, "Apollo Special Electrical" sheets (A. S. & T. P. Co.).

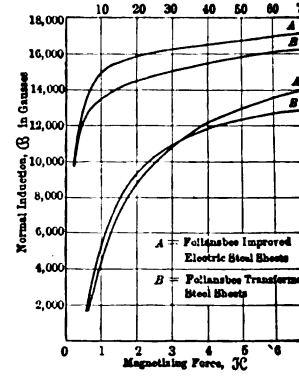


FIG. 26.—Normal induction curves of Follansbee steel sheets.

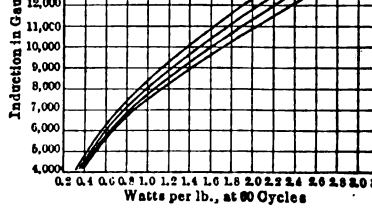


FIG. 27.—Total core loss in Follansbee improved electric steel sheets.

229. Chromium magnet steel usually contains from 2 to 3 per cent. of chromium, and 0.8 to 0.9 per cent. of carbon. The addition of small amounts of tungsten to chromium steel results in no appreciable benefits to the magnetic properties, and therefore, is never made. Quenching of chromium magnet steel is frequently done in oil, and at somewhat lower temperatures

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than for tungsten steel, ranging between 1,475 to 1,525 deg. fahr. If quenched in water, still lower temperatures are used; viz., 1,450 to 1,500 deg. fahr.; water quenching, however, tends to result in more or less hardening breakage. For oil-hardened specimens, common magnetic values are, residual flux = 9,500 and coercive force = 63, with H max. of 300 gausses.

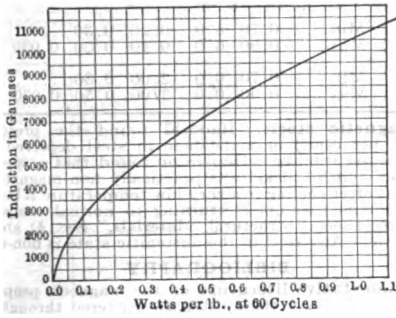


FIG. 28.—Total core loss in No. 29 gage (0.014 in.) Follansbee transformer steel.

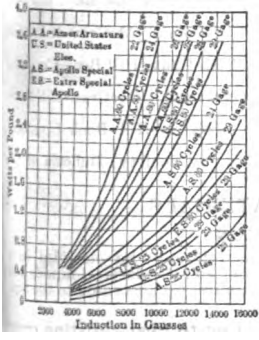


FIG. 29.—Curves of total core losses in electrical sheets.

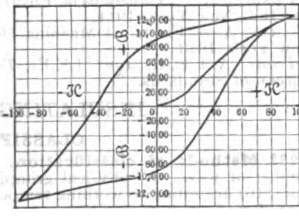


FIG. 30.—Hysteresis loop of glass-hard steel wire.

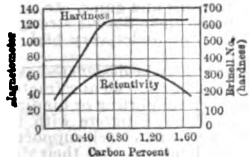


FIG. 31.—Hardness and retentivity of carbon-steel.

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230. Chemical analysis of tungsten and chrome magnet steels recommended limits
(Data from Halcomb Steel Co.)

Steel	Range	C	W	Cr	Mn	P	S	Si
Tungsten	Min	0.70	5.0	0.20	0.30	.....	.....	.....
	Max	0.90	6.0	0.40	0.50	0.030	0.030	0.03(
Chromium	Min	0.70	0.0	2.00	0.30	.....	.....	.....
	Max	0.90	0.0	3.00	0.50	0.030	0.030	0.03(

231. Non-magnetic steels. Hadfield found the presence of larg proportions (12 per cent.) of manganese in steel deprived the metal o nearly all of its susceptibility. Hopkinson found that a specimen of stee containing 25 per cent. of nickel was practically non-magnetic at ordinar temperatures, but after cooling to a very low temperature it became strongl magnetic and remained so upon returning to normal temperature. Th self-hardening steels (see "Structural Materials," Sec. 4) are also practi cally non-magnetic. Any steel in the austenitic state is non-magnetic.

BIBLIOGRAPHY

232. The authoritative literature on the magnetic properties of iron steel and other metals is for the most part scattered through many book dealing primarily with other topics, and through the transactions of th leading engineering and scientific societies and the technical press. Th following is a selected list of the more important works and sources.

EWING, J. A.—"Magnetic Induction in Iron and Other Metals." London 1900, 3rd rev. ed.

STEINMETZ, C. P.—"Alternating-current Phenomena." McGraw-Hill Bool Co., Inc., New York, 1908.

KARAPETOFF, V.—"The Magnetic Circuit." McGraw-Hill Book Co., Inc New York, 1911.

PENDER, H.—"Principles of Electrical Engineering." McGraw-Hill Bool Co., Inc., New York, 1911.

GRAY, A.—"Electrical Machine Design." McGraw-Hill Book Co., Inc. New York, 1913.

Trans. A. I. E. E. *Jour.* I.E.E.; *Trans.* Faraday Society; Bulletin of th Bureau of Standards.

INSULATING MATERIALS

CLASSIFICATION

233 Methods of classification. Dielectrics may be classified in number of ways: (a) physical grouping, under solids, plastics, liquids an gases; (b) according to working temperature limits; (c) according to the typ of application.

234. Classification of dielectrics according to heat-resisting properties. Messrs. Steinmetz and Lamme in their A. I. E. E. paper on "Tem perature and Electrical Insulation" (1913, Vol. XXXII, p. 79) classif the usual insulating materials as follows, in three general classes.

Class A. This includes most of the fibrous materials, as paper, cotto etc., most of the natural oil resins and gums, etc. As a rule, such material become dry and brittle, or lose their fibrous strength under long-continue moderately high temperature, or under very high temperature for a shor time.

Class B. This includes what may be designated as heat-resisting material which consist of mica, asbestos, or equivalent refractory materials, frequentl used in combination with other supporting or binding materials, the deteri ration of which, by heat, will not interfere with the insulating properti of the final product. However, where such supporting or binding materia are in such quantity, or of such nature, that their deterioration by heat wi greatly impair the final product, the material should be considered as belon ing to class A.

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Class C. This is represented by fireproof, or heat-proof materials, such as mica, so assembled that very high temperatures do not produce rapid deterioration. Such materials are used in rheostats and in the heating elements of heating appliances, etc.

The temperature limits specified by the A. I. E. E. Standardization Rules (Sec. 24, Par. 188) are as follows:

(*A*–1) Cotton, silk, paper and other fibrous materials, not so treated as to increase the temperature limit, 95 deg. cent.

(*A*–2) Same as *A*–1, but treated or impregnated, and including enameled wire, 105 deg. cent.

(*B*) Mica, asbestos or any other material capable of resisting high temperature, in which any class *A* material or binder, if used, is for structural purposes only, and may be destroyed without impairing the insulating or mechanical qualities, 125 deg. cent.

(*C*) Fireproof and refractory materials, no specified limit.

235. Physical Classification of Dielectrics

Dielectrics	Solids	Natural	Gums and resins
			Asbestos
			Wood
			Soapstone
			Slate
			Marble
			Lava
			Mica
		Fabricated	Papers and sheets
			Fabrics and yarns
			Hard rubber
			Synthetic resins
			Molded compositions
			Glass
			Vitrified materials
	Plastics		Caoutchouc
			Gutta percha
			Pitches
			Asphalts
			Waxes
			Compounds
	Liquids	Used as such	Mineral oil
			Animal oil
			Vegetable oil
		Solidified on application	Varnish
			Shellac
			Paint
			Enamel
			Japan
	Gases		Atmospheric air
			Hydrogen
			Nitrogen
			Carbon dioxide

236. Classification of dielectrics according to type of application. Under this classification can be named: (1) Wire insulation; (2) cable insulation; (3) insulating supports, combining dielectric properties with mechanical strength; (4) coil and slot insulation for electrical apparatus and machinery; (5) insulating sheets, slabs and barriers; (6) molded insulation, shaped under the application of heat and mechanical pressure; (7) impregnating and filling compounds; (8) superficial paints and varnishes; (9) fluid insulators; (10) gaseous insulators.

237. Use of trade names in connection with insulating materials has unfortunately become very common. On account of the great number of such names no attempt has been made to state or define them all. Wherever possible, insulating materials have been grouped and described in accordance with a rational classification, and adhering if possible to the natural or descriptive name of each thing instead of its trade name.

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DISCUSSION OF PROPERTIES

238. Desirable characteristics of dielectrics may be enumerated as follows, under four heads: (1) electrical, (2) mechanical, (3) thermal, (4) chemical.

(1) Electrical

(a) Great resistivity.
(b) Small surface leakage.
(c) Great disruptive strength.
(d) Desirable magnitude of dielectric constant depends upon types of application.
(e) Small dielectric absorption.
(f) Small dielectric hysteresis.
(g) Minimum power factor.
(h) Minimum temperature coefficients.

(2) Mechanical

(a) Great tensile strength.
(b) Great shearing strength.
(c) Great compressive strength.
(d) Desirable magnitude of modulus of elasticity depends upon type of application.
(e) Desirable degree of hardness—ditto (d).
(f) Not brittle.
(g) Dense non-porous structure.
(h) Non-hygroscopic.
(i) Readily workable.

(3) Thermal

(a) Large specific heat.
(b) Small thermal resistivity.
(c) Small coefficient of expansion.
(d) High softening temp.
(e) High melting point, for solids.
(f) High boiling point and low freezing point, for liquids.
(g) Low viscosity.

(4) Chemical

(a) Stability.
(b) Insoluble in acids, alkalies and oils.
(c) High flash point.
(d) High fire point.

239. Insulation resistance is separable into two components, volume resistivity and surface resistivity. The leakage path through the substance or interior of the dielectric is electrically in parallel with the surface leakage path composed of a film of moisture or oil (with the frequent addition of dust or foreign matter) on the surfaces of the dielectric. For exhaustive discussion of the characteristics of insulation resistance and the insulating properties of dielectrics see the following:

Evershed, S. "The Characteristics of Insulation Resistance;" *Journal* I. E. E., 1913.

Curtis, H. L. "Insulating Properties of Solid Dielectrics;" Scientific Paper No. 234, Bureau of Standards, 1915.

Fleming and Dyke. "On the Power-factor and Conductivity of Dielectrics;" *Jour.* I. E. E., 1912, Vol. XLIX, No. 215, pp. 323 to 431.

240. Volume insulation resistance of dielectrics is dependent upon the resistivity, usually expressed as volume resistivity in ohm-cm., or megohm-cm. for greater convenience. Practically all dielectrics have a negative **temperature coefficient,** or decreasing resistance with rising temperature. When the volume resistivity becomes very high, on the order of 10^{13} ohm-cm, the dielectric absorption current is likely to be of sufficient relative magnitude to influence the observed value of volume resistivity unless sufficient time is allowed for complete electrification. In the case of two materials having a resistivity of 10^{17} ohm-cm., hard rubber and fused quartz, the apparent resistivity under continuous electrification increases for a long time.

For most practical cases, however, that portion of the leakage current which flows through the body of the dielectric is negligible in comparison with the portion which flows through the surface film. But when the volume resistivity is less than 10^{14} ohm-cm. and when the insulator is placed in an atmosphere having a humidity of less than 25 per cent., the greater part of the current may flow through the body of the insulator.

In porous materials or those containing appreciable moisture, such as slate and marble, the volume resistivity decreases somewhat with increase of applied voltage. In all such cases the volume resistivity increases rapidly as the moisture is dried out.

The effective resistance with alternating currents is usually less than with continuous currents, and decreases progressively as a rule with increase of frequency, owing to dielectric energy losses (Par. 251).

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241. Surface insulation resistance. The surface conductivity is the reciprocal of the surface resistivity, and the **surface resistivity** is the resistance between two opposite edges of a surface film which is 1 cm. square. Since for most materials under ordinary conditions of humidity the surface resistivity is much lower than the volume resistivity, the resistance per centimeter length between two linear conductors 1 cm. apart, pressed upon the surface of a slab of the material, is approximately equal to the surface resistivity.

The relationship between surface resistivity and humidity, for a number of different materials, is given in Fig. 32. These curves are generally typical of solid dielectrics. The surface resistivity is often a million times as great at low humidity as at high humidity. Measurements made on various molded compositions at the Bureau of Standards (Scientific Paper No. 234) gave values ranging from 10^{16} to 10^{17} ohm-cm. (between opposite edges of a film 1 cm. square), at 22 deg. cent.

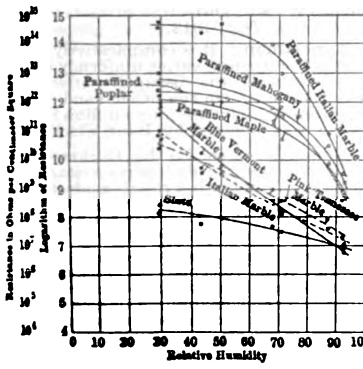


FIG. 32.

242. Dielectric constant is defined in Sec. 2. The customary medium of reference is almost universally dry air at normal temperature and pressure. For most materials the temperature coefficient is positive, but for india-rubber it appears to be negative at ordinary temperatures. The coefficient for celluloid at 15 deg. cent. is approximately 0.005 per deg. cent., whereas for mica it is about 0.0006.

243. Dielectric absorption is the term applied to the apparent soaking up of electric charge within the body of a dielectric when the electric stress is prolonged for an appreciable time. In other words, it requires appreciable time for the dielectric to become fully saturated with electric charge or displacement, when a steady stress is applied. In some materials this phenomenon is marked, while in others it is slight. Due allowance should be made for it, however, in certain classes of measurements, notably insulation resistance.

244. Dielectric strength, usually expressed in volts or kilovolts (kv.) per mil or per mm.,* is a property which it is impossible to determine with high precision, and which is affected by numerous variables such as the size and shape of the test electrodes, the time rate at which the test voltage is raised to the disruptive point, the order of frequency of the test voltage and the thickness of the test specimen. Furthermore, disruptive discharge requires not merely a sufficiently high voltage, but a certain minimum amount of energy. There is no accepted standard apparatus or method for testing dielectrics, and hence the results obtained by different investigators are comparable only as to general order of magnitude, if at all. Moreover the probable error in measurements of disruptive strength is unusually large and any one set of observations is likely of itself to be in error by as much as plus or minus 10 to 20 per cent. Consequently the values of disruptive strength stated in this section are to be considered as purely approximate and not accurately comparative.

245. The factors affecting dielectric strength may be stated as follows; internal or external heating, chemical change, absorption of moisture,

* 1 volt per mil = 39.4 volts per mm.
1 volt per mil = 0.394 kv. per cm.
1 volt per mm. = 0.0254 volt per mil.
1 kv. per cm. = 2.54 volts per mil.

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nature of surrounding medium, size and shape of test electrodes, thickness test specimen, time rate of applying the disruptive voltage, whether co tinuous or alternating test pressure is employed, and order of magnitu of the test frequency.

246. Effect of size of electrodes. Farmer concluded from his tests th the average dielectric strength of insulating materials in *thin* sheet form materially higher with small electrodes than with large ones; upon maki the electrodes very small, such as needle points, however, the dielect strength apparently decreases again. See Farmer, F. M., "The Dielect Strength of Thin Insulating Materials;" *Trans.* A. I. E. E., 1913, Vol. XXX pp. 2097 to 2131. Also see Franklin, W. S., "Dielectric Stresses from t Mechanical Point of View;" *Jour. Franklin Inst.*, 1913.

247. Effect of thickness of test specimen. It is comparatively rare find an insulating material whose dielectric strength varies uniformly with thickness. In the case of fibre, for example, the disruptive strength i creases very slowly with increasing thickness. On the other hand, the di ruptive strength of multiple layers of glass with intervening oil films is near proportional to the thickness. A law was proposed by Baur which can expressed $E = kl^{\frac{1}{2}}$, where E is the disruptive voltage, l is the thickness of t dielectric and k is a constant; in other words, the disruptive voltage var as the two-thirds power of the thickness. This law is a rough guide for so materials. Another law proposed by Walter, for air, is $E = a + bl$, whe a and b are constants and l is the thickness; this law holds for needle ga from 50 to 450 mm. under ordinary pressures and temperatures.

248. Lamination. Hendricks* states that a finely laminated structu improves the dielectric strength. This is partly explained as follows: we spots in successive layers very rarely coincide in position, rupture at so local internal point may be confined to one lamination, and thin materi are in general superior in point of electric and mechanical unit strength.

249. Effect of frequency. There is usually considerable differen between disruptive strengths as determined by alternating e.m.fs. and continuous e.m.fs. In the case of continuous e.m.fs. there is much less i ternal heating than there is with alternating e.m.fs. Disruptive strengt of solid dielectrics measured with continuous e.m.fs. are about one and on half to two times the strengths measured with alternating e.m.fs. under like conditions. When the order of frequency is increased from commercial power frequencies to those representative of high-frequency high-power surges, say 200,000 cycles, there is reason to believe that the disruptive strength is reduced. Creighton has shown that this is the fact in the case of porcelain (see *Proc.* A. I. E. E., May, 1915, p. 819, Fig. 29), where disruptive values at very high frequency were on the order of 60 to 80 per cent. of the 60-cycle values.

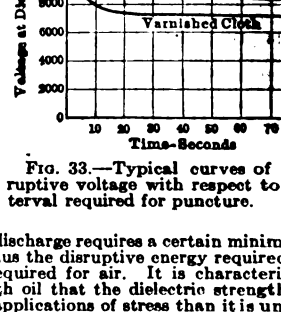


FIG. 33.—Typical curves of d ruptive voltage with respect to i terval required for puncture.

250. Effect of the time element in applying the disruptive pressure is pronounced. For very brief periods dielectrics will withstand much greater potentials than for longer periods. This is apparently a consequence, in part at least, of the fact that disruptive discharge requires a certain minimu amount of energy in each instance. Thus the disruptive energy required the case of oil is about 30 times that required for air. It is characteris of oil and of materials impregnated with oil that the dielectric strength greater for instantaneous or very brief applications of stress than it is und prolonged stress. The brief time interval required to energize the dielectr

* Hendricks, A. B., Jr. "High-tension Testing of Insulating Materials *Trans.* A. I. E. E., 1911, Vol. XXX, p. 167.

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before breakdown occurs is sometimes referred to as the dielectric spark lag. A good illustration of the comparative effects of slow versus fast rate of application of the disruptive voltage is given by Creighton for porcelain (see *Proc.* A. I. E. E., May, 1915, p. 818, Fig. 28). Also see Hayden and Steinmetz, "Disruptive Strength with Transient Voltages;" *Trans.* A. I. E. E., 1910, Vol. XXIX, pp. 1125 to 1158. Fig. 33 shows typical curves (plotted from Rayner's 1912 paper, *Jour.* I. E. E.) of disruptive voltage with respect to the time required for puncture.

251. Dielectric hysteresis is a form of energy loss in dielectrics, and is independent of any loss due to pure conduction. The latter loss is expressed by gE^2, where g is the total conductance in mhos of a given body of dielectric and E is the impressed difference of potential in effective volts, the power loss given thereby being expressed in watts. The **static component** of dielectric hysteresis probably is proportional to the 1.6th power of the maximum dielectric flux density. The **viscous component** of dielectric hysteresis follows the square law. The latter component is probably the predominating one, since experimental evidence* from condenser tests with alternating currents goes to show that the angle of phase difference due to hysteresis is a constant, for any particular condenser. It follows from this that the power loss in the dielectric is proportional to the square of the flux density and the square of the frequency, which corresponds to the viscous component of hysteresis. As a rule these electrostatic hysteresis losses in a condenser are much smaller than the losses occasioned by magnetic hysteresis and are rather difficult to measure. Frequently they amount to no more than a fraction of 1 per cent. of the volt-ampere input of the condenser, at frequencies from 25 to 125 cycles. See Rayner, E. H., "High-voltage Tests and Energy Losses in Dielectrics;" *Jour.* I. E. E., 1912, Vol. XLIX, No. 214, pp. 3 to 89; also see Fleming and Dyke, "On the Power-factor and Conductivity of Dielectrics;" *Jour.* I. E. E., 1912, Vol. XLIX, No. 215, pp. 323 to 431.

252. Dielectric power-factor. When a dielectric is subjected to a periodic alternating e.m.f. less than the disruptive value there is a loss or expenditure of energy within the dielectric from two causes: (1) the leakage conduction current, (2) the dielectric hysteresis. Consequently, the volt-ampere input to the dielectric, instead of having a zero power-factor as in the case of the ideal dielectric of infinite resistance and zero hysteresis, has a power-factor of finite value but usually small magnitude. This total dielectric loss may, in some cases, have considerable importance. Fleming and Dyke* made tests on eleven different materials at 920, 2,760 and 4,600 cycles, and found that the power-factor was less than 1 per cent. in the case of dry Manila paper, paraffin wax, mica, ebonite, pure india-rubber, vulcanised india-rubber and sulphur; about 2 per cent. for glass and gutta percha; and 8 per cent. for dry slate.

253. Effects of temperature. If a dielectric contains moisture, the application of heat will reduce the moisture content and simultaneously increase the resistivity and the disruptive voltage. In the case of a thoroughly dry substance, however, increase of temperature has the reverse effect. Prolonged heating of a dielectric, if in excess of the safe or conservative limit of working temperature, is injurious and tends to hasten the breakdown of the material by disintegration or chemical change, and ensuing disruptive failure. Except in the case of fireproof and refractory materials, the working temperature is a most important factor in determining the life of insulation. See Par. **234** and also see the temperature limits specified in the Standardization Rules of the A. I. E. E., Sec. 24, Par. **187** to **200**.

SOLID NATURAL MATERIALS

254. Asbestos is a mineral fibre comprised of hydrous silicate of magnesia, which melts at a temperature in the range from 1,200 to 1,300 deg. cent. It is useful as an insulating material because of its heat-resisting qualities, and is fabricated into boards, paper, tape, etc., frequently in combination with a binder to make it stronger mechanically and less absorbent of moisture. It is not inherently a good insulator, and for this reason is frequently mixed with other fibres or loading material to impart greater strength, higher insulation and better finish. The commercial varieties of asbestos often

*Steinmetz, C. P. "Alternating-current Phenomena;" New York, McGraw-Hill Book Co., Inc., 1908; 4th ed., pp. 212 and 213.

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contain iron and other impurities, making it almost useless as an electrical insulator. Asbestos is an excellent thermal insulator. Its electrical resistivity is on the order of 16×10^4 ohm-cm.; disruptive voltage, 60 to 100 volts per mil; maximum working temperature, 500 to 600 deg. cent. When used for arc defectors in controllers, switches, etc., it is usually impregnated with a solution of silicate of soda and then subjected to heavy pressure.

Asbestos is frequently combined with magnesium carbonate, or with finely ground sponge, or with wool felt, as a thermal insulation for steam pipes; it is also mixed with cattle hair, for similar use, and known as asbestos hair felt. Asbestos is also extensively employed in the manufacture of molded compositions designed to withstand high temperatures.

255. Chalk is a fine-grained limestone of marine origin, composed of finely comminuted shells, particularly those of the foraminifera. The specific gravity may be as low as 1.8. A theoretically pure limestone is merely a massive form of the mineral calcite, consisting entirely of calcium (lime) carbonate, $CaO + CO_2 = CaCO_3$, or 56 per cent. CaO and 44 per cent. CO_2.

256. Fire clay. Clay is the term applied to fine-grained unconsolidated natural materials which possess plasticity when wet, but lose it on being heated and become hard. The specific gravity ranges between 1.5 and 2.2. The clays are composed essentially of silica and alumina, in a state of exceedingly fine subdivision, resulting from the decay of older rocks. Fire clay is the variety of clay which is most highly refractory, containing much silica and little lime, iron or alkalies. As an insulator it is applied in semi-liquid form and baked, after the conductors are imbedded. It is not affected by acids, oils or alkalies.

257. Gums and resins. The natural gums and resins such as caoutchouc, gutta-percha, pitch, etc., are seldom if ever employed for insulating purposes while in their native condition, but are treated, or mixed with other materials, or adulterated, in a great variety of ways. They form the bases or constituents of many different insulating compounds, but undergo numerous chemical or physical changes in manufacture.

258. Ice. The disruptive strength of ice is 11 kv. (max.) per cm.; dielectric constant, 86.4; resistivity, 7.2×10^7 ohm-cm. See Thomas, P., "The Dielectric Properties of Non-conductors;" *Jour. Franklin Inst.*, 1913, Vol. CLXXVI, pp. 283 to 301. According to Whittaker's Pocketbook, **pure water** has a resistivity of 7×10^{12} ohm-cm.

259. Ivory has a resistivity at 22 deg. cent. of 2×10^6 ohm-cm.

260. Kaolin is a white china clay whose chief ingredient is the **mineral** kaolinite, and the latter has the chemical composition $H_2Al_2Si_2O_8 + 1H_2O$, or hydrous silicate of aluminum. Kaolin is highly refractory and is one of the principal materials employed in the manufacture of porcelain. It is sometimes employed for insulating purposes.

261. Lava is a mineral **talc**, which has the chemical composition $H_2Mg_3Si_4O_{12}$, or hydrated magnesium silicate, and is similar to soapstone, pumice and talc. It is slightly soluble in hydrochloric acid, but is not attacked by other acids or alkalies. While in the natural state it can be machined with the same facility as brass. It neither shrinks nor expands under the influence of moisture and has a very small coefficient of expansion.

After machining, it is baked at about 1,100 deg. cent. which renders it extremely hard. Its insulating resistance is high and according to tests made by the American Lava Co., its dielectric strength varies from 3,000 to 10,000 volts per mm., according to the thickness. See Par. **270** and **271**.

262. Lavite (also see lava) is a light buff or cream-colored insulating material invented and patented in 1885 by D. M. Steward. The manufacturers supply the following information: Density, 2.5 to 2.7; electrical resistivity, 500 to 2,500 megohm-cm.; disruptive strength, 200 to 250 volts per mil; modulus of rupture, 6,000 to 12,000 lb. per sq. in.; compressive strength, 20,000 to 30,000 lb. per sq. in.; compares with glass in hardness; not affected by temperatures up to 1,000 deg. cent.; unaffected by acids except aqua regia.

263. Marble is a limestone of the crystalline variety which will take a high polish and exhibit pleasing color effects. Its chief constituents are lime and magnesia, or their carbonates; it also contains water of formation and sometimes metallic veins. It is used very extensively for low-tension

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switchboard panels. Its properties can be improved by treatment in molten paraffin wax or linseed oil, after all moisture has been expelled, but such treatment results in discoloration. The resistivity is on the order of 10^3 to 10^4 megohm-cm. and the disruptive voltage is in the vicinity of 50 to 100 volts per mil. See tests in Par. **269**.

264. Mica is generally recognised as the most superior insulating material known to the art, that which is imported from India being the best, the Canadian grades next and domestic varieties last. Either domestic or India mica is satisfactory for nearly all insulating purposes except for commutators, where it is too hard to wear down as fast as the copper bars. For the latter service Canadian amber mica is considered more satisfactory, being softer than the other grades. All grades of muscovite (white) mica are considered suitable for electric heating appliances. Mica sheets and washers are used in electrical apparatus and appliances in almost innumerable shapes. Cut mica in sheets becomes very expensive in the larger sizes, the largest commercial listed size being 8 in. by 10 in. On this account it is customary to build up larger sizes by connecting together thin layers of mica. Such manufactured mica plate takes a number of forms.

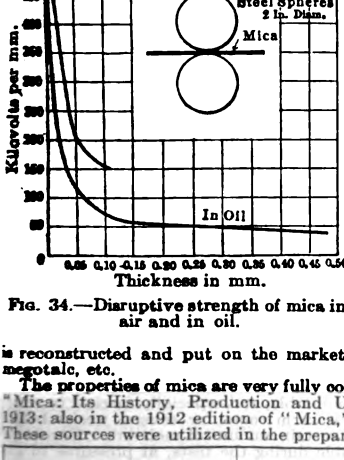


FIG. 34.—Disruptive strength of mica in air and in oil.

265. Composition and properties of mica. Mica is a refractory mineral constituted of the double silicate of alumina or magnesia, and potash or soda, combined with varying proportions of potash, soda and other impurities. Iron in excess colors it gray and black; magnesia tends to darken the color; aluminium and potassium silicates tend to make the mica transparent. Mica crystallizes in laminated form and may be split along its axis to sheets as small as 0.006 mm.

It has a high dielectric strength and is suitable to withstand high temperatures. However, in its natural state it is not flexible nor uniform, and permits large surface leakage; so that most mica is reconstructed and put on the market in the form of micanite, megomit, megotalc, etc.

The properties of mica are very fully covered in a publication by Zeitler, H, "Mica: Its History, Production and Utilization;" D. Jaroslaw, London. 1913: also in the 1912 edition of "Mica," by the Canadian Dept. of Mines. These sources were utilized in the preparation of the following table.

Origin	Resistivity in 10^{13} ohm -cm.	Dielectric constant	Disruptive strength in volts per mm.*
Madras	15 to 133	2.5 to 5.5	50,000 to 80,000
Bengal	7 to 118	2.8 to 4.7	40,000 to 120,00
Canada	0.44 to 22	2.9 to 3.0	80,000
South America	39	5.9	40,000 to 90,000

Fleming and Johnson give the dielectric strength, in sheets 2 to 3 mils thick, as about 2,000 volts per mil for amber mica and about 3,000 to 4,000 volts per mil for the white, ruby and soft green varieties; Fig. 34 shows the

* NOTE.—Test thickness, 0.3 mm.

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results of tests made by Rayner at the National Physical Laboratory (*Jour.* I. E. E., 1912, Vol. XLIX, No. 212). Power-factor at 920 cycles, 0.001. The density of mica is from 2.7 to 3.1. Specific heat, 0.206 to 0.208. It is not affected by heat until a temperature of several hundred degrees centigrade is reached, when the laminæ separate in the harder varieties and tend to disintegrate into small scales or flakes; amber mica is less affected. Melting-point, 1,200 to 1,300 deg. cent. It will withstand great mechanical pressure perpendicular to the plane of cleavage.

266. Mica products. Many products are manufactured from mica, including paper, cloth, plate and molded insulation. In some cases the strips of mica are mounted on paper or cloth, in alternate layers, using an insulating binder such as shellac. Molded products are usually made from ground mica mixed with a binder, and sometimes mixed with other insulating materials such as asbestos, or a gum or compound.

267. Quartz is a form of **silica** (SiO_2) occurring in colorless transparent hexagonal crystals, but sometimes yellow, brown, purple, green and other colors. It also occurs in crystalline masses of vitreous luster. Density, 2.65. Dielectric constant 4.3 to 5.1. The resistivity is from 10^{16} to 10^{17} ohm-cm. Silica is the principal constituent of glass. Quartz fibres of very small lateral dimensions are sometimes used for suspensions in delicate electrical instruments; such fibres have a tensile strength of about 10×10^9 dynes per sq. cm. Also see fused silica (Par. **278**).

268. Slate is a rock of clay composition, in which pressure has produced a very perfect cleavage, so that it may be split into thin tough plates. The principal constituents are silica and alumina, with small percentages of iron oxides, lime, magnesia, potash and soda. It frequently contains metallic veins, which make it worthless for electrical work. It is hygroscopic, in addition to containing water of formation, and is therefore far from an ideal insulator. The resistivity of a good grade of slate at normal temperature is of the order of 10^2 to 10^4 megohm-cm., and decreases rapidly at high temperatures; higher values of resistivity have been obtained with very dry specimens. The dielectric constant is between 6 and 7. Power-factor at 920 cycles, 0.086. The disruptive voltage for 1 in. of thickness is from 5,000 to 10,000 volts, or 5 to 10 volts per mil. See tests in Par. **269**. Specific heat, about 0.2; thermal conductivity, 0.0036 g-cal. per cm-cube per deg. cent. per sec. The density is from 2.7 to 2.9. Slate is a satisfactory insulator where a non-combustible, low-tension material having fair insulating properties is required. It is sometimes varnished or enamelled to keep out moisture.

269. Puncture tests of Vermont slate and marble,* made with flat circular brass electrodes 0.785 in. in diameter having slightly rounded edges, indicated values ranging from 50 volts to 100 volts per mil for marble (test pieces 14 in. square and about 1 in. thick) and roughly one-tenth of these values for slate. Blue marble was considered superior to white marble. Marked heating of the specimens was noted at or near the rupturing voltages, being less marked in the case of blue marble, and especially marked in slate; the test pieces were air dried in a warm room for several weeks before testing, but undoubtedly retained a certain amount of moisture. Corona or brush discharges were very noticeable during the tests, at pressures in the vicinity of the rupturing values.

270. Soapstone is a kind of soft stone, which is soapy or slightly oily to the touch. It is also known as **steatite**, or massive variety of **talc**, of grayish-green or brown color. It forms extensive beds and is mined for hearths, sink linings, etc. It is occasionally used for electrical insulation, in the form of slabs or barriers and will withstand very high temperatures. It is soft, not very strong, not affected by acids, oils or alkalies; can be machined, drilled and sawed, and absorbs moisture.

271. Talc is a hydrous magnesian silicate, $H_2Mg_3(SiO_3)_4$, containing when pure 63 per cent. of silica, 32 per cent. of magnesia and 5 per cent. of combined water. It has a specific gravity of 2.6 to 2.9. Soapstone and French chalk are varieties of talc; other varieties are used in making soap, paper, lubricants, etc. See Par. **261**.

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* Report of the Vermont State Geologist, 1912, pp. 196 to 219.

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272. Wood is used as an insulating material to a considerable extent. The varieties of wood employed are usually the hard woods, such as maple and hickory, impregnated with oil, paraffin wax, or clear air-drying varnish. The resistivity of paraffined wood, at 22 deg. cent. is of the following magnitude: mahogany, 4×10^{12} ohm-cm.; maple, 3×10^{10}; poplar, 5×10^{11}; walnut, 0.09×10^{10} to 1×10^{10} (Scientific Paper No. 234, Bur. of Standards). The dielectric constant and the disruptive voltage are both dependent upon whether the electric stress is parallel or perpendicular to the grain. Parallel to the grain the dielectric constants of red beech and oak are between 2.5 and 4.8; perpendicular to the grain, 3.6 to 7.7.

In maple boiled in transformer oil under vacuum, dried under vacuum and boiled again at atmospheric pressure, the disruptive voltage along the grain, at 1 in. of separation, was 70 kv.; at 2 in. it was 90 kv.; across the grain, at 0.5 in., it was 60 kv.; at 1 in. it was 80 kv.; dielectric constant, at 20 to 25 deg. cent., across grain, 4.1. Well-dried wood should stand 10 kv. per in. without signs of burning or heating. It is extremely important that the wood should be well dried before impregnation, because it is very difficult to remove the moisture subsequently. When wood contains moisture it is a relatively poor insulator and the water contained in the cells conducts electrolytically. Wood treated with zinc chloride to protect it against decay has comparatively low resistivity; see *Electrical World*, 1911, Vol. LVII, p. 828. For curves of disruptive strength of maple see Hendricks, A. B., "High-tension Testing of Insulating Materials;" *Trans.* A. I. E. E., 1911, Vol. XXX, pp. 167 to 213.

VITRIFIED MATERIALS

273. Glass is an insulating material in very extensive use, possessing high resistivity and dielectric strength at ordinary temperatures. The principal constituent is silica, ranging from 50 to 75 per cent. of the total contents; potash, soda, lead oxide and lime are also present, in various proportions. The resistivity at ordinary temperatures is on the order of 10^{13} to 10^{16} ohm-cm. and decreases with great rapidity as the temperature increases. Gray and Dobbie found that potash glass has higher resistivity than soda glass, and annealing increases the resistivity (*Proc.* Royal Soc., 1900, Vol. LXVII, p. 197). At very high temperatures glass becomes a fairly good conductor. Moisture readily condenses upon its surface and it has consequently a high surface leakage. It is also soluble in water to a slight degree and under weather exposure the surface tends to roughen. The dielectric constant ranges from about 5.5 to 10. The dielectric strength ordinarily ranges from 150 to 300 volts per mil, and is higher in very small thicknesses. At 920 cycles crown glass has an apparent resistivity of 17×10^{9} ohm-cm.; dielectric constant, 6.60; power-factor, 0.018. Mechanically glass is unreliable and brittle; the tensile strength is uncertain and anywhere from 1,000 to 10,000 lb. per sq. in., with somewhat higher compressive strength. Coefficient of linear expansion, 0.000008 to 0.0000095 per deg. cent. Density 2.5 to 4.5. For information on glass manufacture see Rosenhain, W., "Glass Manufacture," D. Van Nostrand Co., New York.

274. Porcelain. The three principal constituents of electrical porcelain are feldspar, clay and silica. There are three feldspars: orthoclase, or potash feldspar, which is the most important; albite or indianite, which is soda feldspar; anorthite, or lime feldspar. The two clays used are ball clay, and china clay or kaolin. A standard mixture of these constituents for testing purposes is 20 parts feldspar, 50 parts kaolin and 30 parts quartz. The function of the feldspar is to act as a flux to unite the other constituents into a vitreous mass when fired. There are two processes of manufacture, the dry process and the wet process. For details on the manufacture and properties of electrical porcelain, see an exhaustive paper by E. E. F. Creighton, "Electrical Porcelain;" *Proc.* A. I. E. E., May, 1915, pp. 753 to 841. Also see Perrine, F. A. C., "Electrical Conductors;" D. Van Nostrand Co., New York, 1903; Chap. XIII.

275. Dry-process porcelain is manufactured by molding the moist raw mixture under high mechanical pressure and then vitrifying by the usual firing process. This grade of porcelain is usually very porous and consequently has a disruptive strength on the order of atmospheric air, or less. At or near disruptive pressures, however, it heats rapidly and is not suitable for high-voltage insulation. The safe dielectric strength is on the order of 1,000 volts.

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276. Wet-process porcelain is made by mixing the raw ingredients with water. The mixture is placed in a filter press and the surplus water extracted, leaving a wet plastic cake. The cake is re-mixed in a pug mill to make it more homogeneous, then molded or jiggered into a blank of approximate final shape, and allowed to dry. When fairly dry it is turned in a lathe or tooled to final shape, dipped in the glazing bath and placed in the kiln preparatory to firing. The glazing mixture is the same as the porcelain except that it contains more flux, and thus melts at a temperature barely sufficient to vitrify the porcelain. The finished glaze is virtually a species of glass. During manufacture porcelain shrinks from 10 to 20 per cent. and much care is required to proportion the parts so that cracking will not result. The thickness is limited both by the shrinkage and the difficulty of obtaining satisfactory vitrification. High-voltage porcelain is made in all cases by the wet process.

277. Properties of high-voltage porcelain. The density is from 2.3 to 2.5. It is not affected by oils, acids or alkalies; the glaze is said by some authorities to be very slightly soluble in ordinary water. Unglased porcelain should be non-hygroscopic and on immersion should not increase in density. A good rough test is to place a drop of ink on the porcelain and note whether it spreads or penetrates; alcohol solutions are still better. The linear expansion coefficient is from 4.5 to 6.5 $\times$ 10^{-6} per deg. cent. The specific heat is 0.17 and the thermal conductivity is 0.045 per cent. of that of silver. The electrical resistivity of unglased porcelain is on the order of 10^{14} to 10^{15} ohm-cm. at ordinary temperatures, and decreases very rapidly with increasing temperatures; at very high temperatures porcelain becomes a fair conductor, and is therefore unsuitable for electric furnaces.

The dielectric constant is from 4.4 to 6.8 with continuous e.m.f. and about 10 per cent. less at 50 cycles per sec. At low frequencies the disruptive voltage is about 30 kv. for a thickness of 0.1 in. and about 110 to 120 kv. for a thickness of 0.5 in. At frequencies of the order of 200,000 cycles the disruptive strength, for a thickness of 0.5 in., is on the order of 80 to 90 kv. and if the test voltage is applied rather slowly the disruptive strength varies in much smaller proportion than the thickness (see paper by Creighton mentioned below). In some cases mechanical stress has been observed to reduce the disruptive strength, but in other cases had little effect.

American porcelains have a tensile strength which is variously stated from 650 to 2,200 lb. per sq. in., with an average of about 1,400 lb. per sq. in. The compressive strength is about 10 times the tensile strength. Modulus of elasticity, 2,500,000 in-lb. European porcelains are generally reported as having a tensile strength of 4,500 to 6,500 lb. per sq. in. and a compressive strength of about 65,000 lb. per sq. in. The following references on porcelain are given for the convenience of those who wish more complete information.

Kempton, W. H. "The Application of Porcelain to Strain Insulators;" *Trans.* A. I. E. E., 1910, Vol. XXIX, pp. 967 to 974.

Lustgarten, J. "High-tension Porcelain Insulators;" *Jour.* I. E. E., July, 1912, pp. 235 to 288.

Imlay, L. E. and Thomas, P. H. "High-frequency Tests of Line Insulators;"

Sothman, P. W. "Comparative Tests on High-tension Suspension Insulators;" *Trans.* A. I. E. E., 1912, Vol. XXXI, pp. 2143 to 2226.

Austin, A. O. "Factors Producing Reliability in the Suspension Insulator;" *Proc.* N. E. L. A., Hydroelec. and Transmission Sessions, pp. 201 to 223; 1913.

Creighton, E. E. F. "Electrical Porcelain;" *Proc.* A. I. E. E., May, 1915, pp. 753 to 841.

Also see *Trans.* American Ceramic Society.

278. Silica. The properties of **fused silica** are as follows: Resistivity at ordinary temperatures, on the order of 10^{14} to 10^{19} ohm-cm., decreasing rapidly at higher temperatures; dielectric constant, 3.5 to 3.6; dielectric strength, above 600 volts per mil; melting-point, 1,700 to 1,800 deg. cent.; coefficient of expansion, 0.0000006; density, about 2.07. Also see *Chemical Abstracts*, Vol. IV, p. 866, and Vol. VII, p. 3443.

279. Tile. Vitrified clay tile is very extensively used for underground conduits. Although it possesses very fair insulating properties, its use for this purpose is owing very largely to its immunity from corrosion and disintegration under sub-soil conditions and also its ability to withstand a great

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range of temperatures without injury. As a rule, it is slightly absorbent, receiving as much as 3 or 4 per cent. of water, in some cases, in 24 hr. The puncture voltage, with a 0.6-in. (1.5 cm.) wall, after 24-hr. immersion, ranges from about 16,000 to 30,000 volts. It is not affected by arcs unless in direct contact with them, and in that event will be likely to melt locally and chip or fracture in the surrounding area in consequence of unequal heating and expansion.

280. Vitreous enamel consisting of opaque white glass is extensively used for coating iron resistor grids and imbedding the resistor wires, thus forming non-inflammable and highly fireproof devices capable of withstanding unusually high operating temperatures. Enamelled iron-ware is made extensively by the process of sprinkling powdered glass upon red-hot metal, whereupon the glass fuses and forms a continuous thin coating. The formulas used for compounding the glass are quite closely guarded as manufacturing secrets. What is desired is a thin, strong elastic coating which will expand and contract with temperature changes at as nearly as possible the same rate as iron.

FIBROUS MATERIALS

281. Cellulose is the base of practically all fibrous insulating materials and is an organic compound composed of 48 per cent. carbon, 46 per cent. oxygen and 6 per cent. hydrogen. It is a carbohydrate of the formula $(C_6H_{10}O_5)_x$, similar in composition to starch. When pure it is a white amorphous mass; unsized, well-bleached linen paper is nearly pure cellulose. It has a resistivity on the order of 10^8 to 10^{10} ohm-cm. at ordinary temperatures and a dielectric constant of about 3.9 to 7.5. All untreated cellulose materials break down at about 120 deg. cent. and should not be subjected to a maximum of more than 95 deg. cent. A safe operating limit is about 80 deg. cent.

282. Untreated fibrous materials are as a whole hygroscopic and are therefore relatively inferior insulating materials. They are nevertheless employed, some of them, to a great extent, but their use is very largely confined to conditions under which moisture is restricted or expelled. Their properties are greatly improved by treatment or impregnation.

283. The impregnation of fibrous and asbestos products with varnishes, gums, bakelite, etc., produces several results: First, the treating materials fill up the pores of the basic material and eliminate moisture; second, the dielectric strength is increased even where there is no moisture to be considered; third, most treating materials assist in producing smooth surfaces; fourth, the heat-resisting quality of the basic material is often increased, and, fifth, the filling up of the pores may in certain cases reduce the tendency to shrink. Incidentally the treating materials increase the heat conductivity of the insulation, resulting in better radiation.

284. Paper is manufactured from wood pulp, rags or plant fibre. The essential processes in manufacture are (1) the reduction of the raw material to the consistency of a thin pulp, by means of operations involving the use of chemicals and steam; (2) the running of this pulp upon a continuous sieve of fine mesh, which retains the fibres that become felted together; (3) the removal, drying and finishing of the felt so formed. Finished paper retains traces of the bleaching or coloring matter employed, and in addition frequently contains a certain amount of loading matter such as china clay, calcium sulphate and other inert mineral matter. A sizing of vegetable or mineral solution is sometimes added to render the paper less porous and improve the surface.

The mechanical properties of paper are derived in large degree from the basic fibres employed in its manufacture; thus paper made from wood pulp is brittle and easily torn, whereas linen or Manila fibre produces a much tougher and stronger paper. Owing to its porosity paper is hygroscopic and normally contains from 7 to 12 per cent. of moisture. When thoroughly dry it has a very high resistivity, on the order of 10^{15} ohm-cm., but it easily absorbs water and when wet descends to the class of a poor conductor. The dielectric constant of dry paper is from 1.7 to 2.6. Dry Manila paper has a power-factor of about 0.007 at 920 cycles. The dielectric strength of various grades of untreated paper, ranging in thickness from 1.8 to 28 mils, should average from 110 to 230 volts per mil; higher values are obtainable from extremely dry paper. The tensile strength will range from a few thousand up

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to many thousand lb. per sq. in., depending upon the quality of fibre. T elongation at fracture is slight, about 2 or 3 per cent. For temperature li its see cellulose, Par. **281**. There are numerous varieties of insulating pap such as rope paper, Japanese paper, Manila paper, whale-bone paper, ful board, pressboard, etc., some of which are briefly mentioned in otl paragraphs.

285. Treated paper is a clear dry paper impregnated with oxidized linse oil, or a mixture such as oxidized oil and asphalt, or a gum-base varni Well-treated papers in thicknesses ranging from 6 to 12 mils break down about 500 to 750 volts per mil. The Mica Insulator Co. gives disruptive v tages for Empire oiled papers, in thicknesses of 1.5 to 18 mils, ranging fr 1,740 to 800 volts per mil; these values include condenser, rope, bond a cement paper and fuller board. The same manufacturer gives for rope pa treated with a compound of oxidised oil and asphalt, disruptive volta ranging from 1,600 to 600 volts per mil, corresponding to thicknesses of 5 15 mils. According to Jona, the dielectric strength of impregnated pa cable insulation is from 200 to 250 volts per mil, and the dielectric constan about 2.5 to 4. The value of the constant k (see Par. **292**) for impregnat paper is usually between the extremes of 1,000 and 3,000.

286. Bakelized paper, known under the trade name of bakelite-micar is a dark, hard, homogeneous material considerably stronger than hard fib It can be worked with sharp tools, punched only in thin sheets, and cannot molded. It will withstand continuously a temperature of 150 deg. cent. a for short periods 260 deg. cent. It is infusible. The density is about 1.: Moore gives the following properties of bakelite-micarta, measured at l cycles (see Moore, R. W. E., "Properties and Uses of Bakelite-micarta *Electric Journal*, 1913, pp. 645 to 650): resistivity, 2.13×10^{13} ohm-cr dielectric constant, 5.2; power-factor, 0.024; dielectric strength, 500 1,000 volts per mil; tensile strength, about 20,000 lb. per sq. in.; coefficie of expansion, 0.00002 per deg. cent. It is said to be insoluble in alcohol, be sine, turpentine, weak acids and alkalies, hot water and oils and non-h groscopic.

287. Asbestos paper, comprised of an asbestos base, is a soft, flexil material of little strength and is hygroscopic. It will withstand an operati temperature of 260 deg. cent. without injury. The dielectric strength is on the order of 100 volts per mil.

Treated asbestos paper. A variety of treated asbestos paper known as Delta sheeting is impregnated with a black insulating compound which softens at about 120 deg. cent. and melts at about 200 deg. cent. It is claimed that from 2,500 to 5,000 volts is required to puncture it, in thicknesses of 10 to 25 mils.

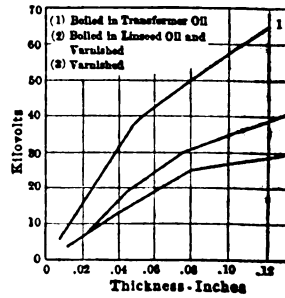


FIG. 35.—Dielectric strength o treated pressboard.

288. Pressboard and fuller board. Pressboard is manufactured from cotton rags and paper clippings, in a number of grades. It is similar to paper, but thicker and less flexible. In the untreated condition it is hygroscopic, and its properties improve with its dryness. Uppenborn gave the resistivity as 11×10^9 ohm-cm. and Turner and Hobart gave the dielectric strength as 200 to 330 volts per mil. Presspalm is another name for pressboard, applied to a grade manufactu in Germany. The qualities of pressboard are greatly improved by impr nation.

289. Treated pressboard. Extensive tests of oiled and varnished pr board are given by Hendricks in "High-tension Testing of Insulat Materials," *Trans.* A. I. E. E., 1911, Vol. XXX, p. 167. The dielectric c stant of pressboard dried and boiled in transformer oil ranges from 4.3 13 deg. cent. to 7.5 at 100 deg. cent. The dielectric constant of varnish

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pressboard is about 2.9 at 20 to 25 deg. cent., measured on 0.1-in. board. The dielectric strength of treated pressboard is given in Fig. 35: curve (1) for pressboard dried and boiled in transformer oil; curve (2) for pressboard dried, boiled in linseed oil and given two coats of varnish; curve (3), dried and given two to four coats of linseed oil and gum varnish, depending on thickness. When these sheets are laid together in laminations, the puncture voltage per mil of complete thickness decreases, but in the case of very thin laminations the puncture voltage does not appear to decrease in as rapid ratio as with single thicknesses.

290. Vulcanised fibre* is a hard, dense material of which the principal ingredient is paper or cellulose made from cotton rag stock; the other ingredients are zinc chloride and coloring matter, the latter consisting of analine colors or mineral pigments. The finished material is heavily compressed into slabs, sheets, tubes, etc. The water and chemicals are not completely removed during manufacture and the product is hygroscopic and not a superior insulating material except for moderate voltages. It will absorb about 50 per cent. of its weight of water in 24 hours. The density ranges from 1.0 to 1.5 according to the grade; average 1.4. The resistivity is comparatively low for dielectrics, or on the order of 10^7 to 10^{10} ohm-cm. Certain varieties are said to have a resistivity as high as 7×10^{13} ohm-cm., probably in a very dry state. The measurements of dielectric strength by different observers are widely discrepant. Parshall and Hobart gave 10,000 volts as the dielectric strength of all thicknesses from $\frac{1}{4}$ to 1 in. Hendricks gave about 200 volts per mil at thicknesses of 50 to 150 mils, 160 volts per mil at 0.4 in., 100 volts per mil at 0.7 in. and 90 volts per mil at 1.0 in. Others have found values ranging as high as 300 volts per mil; the results depend largely on the dryness of the material. The tensile strength ranges from 10,000 to 20,000 lb. per sq. in. and the compressive strength is from 35,000 to 60,000 lb. per sq. in. Fibre is not soluble in water or oil, but is attacked by strong acids, and swells when soaked in water; upon drying it shrinks appreciably and warps badly. Numerous grades of fibre are manufactured and known by various trade names, as horn fibre, hard fibre, indurated fibre, leatheroid, fish paper, etc. The flexible and more fibrous varieties have better insulating qualities. Impregnation improves the qualities in marked degree.

291. Treated fibre. The insulating properties of hard or vulcanised fibre are much improved by treating the pulp with bakelite. A material of this character, known as bakelite-dielecto, is manufactured by The Continental Fibre Co. and is said to have the following characteristics. It is a hard, tough material, light brown or black in color, and manufactured in sheets, tubes and certain special forms; cannot be molded, but can be machined either with or against the grain; is non-hygroscopic and impervious to hot water, oils and ordinary solvents; will withstand continuously a temperature of 150 deg. cent.; resistivity, 1.1×10^{12} ohm-cm. at ordinary temperatures, increasing with temperature up to 100 deg. cent.; dielectric strength, 700 to 1,150 volts per mil; average tensile strength, 18,000 lb. per sq. in.; compressive strength, 21,000 lb. per sq. in.

292. Impregnated fibre duct is in extensive use for both inside and outside construction. It is made in the form of a cylindrical tube by wrapping many layers of paper or pulp on a mandrel and impregnating it during the process with bitumen or a compound of liquid asphalt and coal tar. It is sometimes known as **bitumenized fibre.** Tests made on a certain grade of this material show that it absorbed from 2 to 3 per cent. of water after 96 hr. immersion; one manufacturer guarantees not more than 0.75 per cent. when the ends are sealed. The compound softens slightly at 55 deg. cent. and commences to break down at about 95 deg. cent. Manufacturer's guarantees on minimum puncture voltage, dry, through a 0.375-in. wall, range from 25 to 50 kv; after prolonged immersion the dielectric strength will usually be lowered, depending naturally upon the amount of moisture absorbed.

293. Varnished cloth is a thin white fabric of cotton or linen muslin coated with a mixture of boiled linseed oil, resin and benzine. Upon drying the oil oxidizes in contact with the air and leaves a smooth, hard surface.

* See "Manufacture of Hard Fibre," *Electrical World*, Vol. LIII, p. 1437; also see Vol. LV, p. 1342.

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Successive coats may be added to secure the desired thickness. This material is also known as **varnished cambric** and as **varnished muslin.** For varnished cambric the usual value of the constant k in the formula $R = k \log_{10}(D/d)$ is from 500 to 2,000; R is the insulation resistance of the insulated wire in megohm-miles, d is the diameter of the conductor and D is the outside diameter of the insulation. Dielectric constant, 3.5 to 5.5. Dielectric strength, in commercial thicknesses of 5 to 16 mils, about 500 to 1,300 volts per mil; the Mica Mfg. Co. gives 1,000 volts per mil. Also see tests by Farmer, F. M., "The Dielectric Strength of Thin Insulating Materials;" *Trans.* A. I. E. E., 1913, Vol. XXXII, pp. 2097 to 2131.

Varnished cambric is more elastic than paper and is very suitable for **cable insulation.** A separator of treated paper, cloth or rubber is applied to the copper core to prevent any action of the varnished cambric film on the copper. Then strips of varnished cambric are taped over the separator with applications of a plastic non-hardening compound between layers to exclude moisture and make the cable flexible. The core is finished by cotton braiding and weather-proofing, or asbestos braiding and flame-proofing, or a lead sheath over tape. In some types of cable the insulation is graded, first using rubber and then varnished cambric. The General Electric Co. recommends a working temperature limit of 80 deg. cent. (176 deg. fahr.) for varnished cambric cables.

294. Oiled cloth is a thin, white fabric of cotton or linen muslin coated with two or more applications of pure oxidised linseed oil. The insulating properties are derived chiefly from the oil or compound with which the fabric is impregnated. This material is known by a number of trade names, among them **Empire cloth.** Gray gives the normal dielectric strength, with a 10-mil thickness, as 750 volts per mil; the Mica Insulator Co. gives 1,000 to 1,100 volts before baking and 1,100 to 1,200 volts after baking. Silk, linen, canvas and duck are treated by the same process, with dielectric strengths ranging from 1,100 to 1,450 volts per mil with silk, 1,250 to 1,375 volts per mil with linen and 600 to 775 volts per mil with canvas (Mica Insulator Co.).

295. Impregnated cloth is similar to varnished or oiled cloth, with the difference that the fabric is treated with an impregnating compound. One manufacturer employs a mixture of oxidised oil and asphalt; others use an asphaltum or a paraffin base, dissolved in a thinning material. The Mica Insulator Co. gives puncture voltages for "Kabak" cloth (impregnated cambric) ranging from 1,065 to 1,650 volts per mil.

296. Composite insulation of fibrous materials and mica. In applying mica to coils or heavy strap conductors it is necessary to use some fibrous material like paper or cotton as a base for the mica. It is customary to build up mica on thin sheets of fish paper or Japanese paper, and to wrap the resultant sheet around the straight parts of armature coils or heavy conductors. It is also customary to build up mica on a thin cotton tape and to use the resultant material for taping coils or heavy conductors. If the amount of paper or tape is small and if the material is applied in such a location, as in an armature slot, that the mica will remain intact even after the paper or the cotton tape has deteriorated, these materials may be expected to withstand fairly high temperatures.

297. Paper and mica, or mica paper, is prepared from various grades of paper by coating them with thin mica scales which are made to adhere by means of a cementing varnish such as shellac. The layers of mica and paper are built up in a variety of ways, depending upon the degree of flexibility, or stiffness, desired. Parshall and Hobart give puncture voltages for composite laminæ of alternate paper and mica, ranging from 700 to 1,300 volts per mil, in thicknesses of 5 to 11 mils. Various combinations of paper and mica are manufactured, including Japanese, fish and rope papers and pressboard.

298. Cloth and mica, or mica cloth, is prepared from various fabrics by coating them with a thin layer of mica, cemented together with a cementing varnish like shellac. A layer of paper is sometimes added to the combination. An extra flexible cloth is made by using rubber tissue as a binder, instead of cementing varnish.

299. Cotton insulation for magnet wires, employed more extensively than any other material except enamel, is applied in one, two or three thicknesses. Untreated cotton is hygroscopic and breaks down at a temperature of 120 deg. cent. The thickness of covering varies with the size of wire (se

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tables in Sec. 5). Gray gives the puncture voltage of a 7-mil thickness (composed of two layers) as about 150 volts; impregnated, about 600 volts.

300. Silk insulation for magnet wires is applied in one or two thicknesses, ranging from 1 to 2.5 mils per layer. While it is somewhat hygroscopic in the untreated condition, it has superior insulating properties compared with cotton, and is much improved by impregnation. Neither cotton nor silk are the equal of baked enamel (Par. **351**) in dielectric strength.

301. Asbestos insulation for magnet wires. Asbestos insulation can be applied to wires and small straps with the use of binding materials, but in all cases, except in that of asbestos tape which can readily be used in taping armature or field coils, the mechanical qualities are quite poor. Asbestos windings also require considerable space if used in sufficient thickness, they are not in themselves moisture-proof, they have low dielectric strength, and do not give a smooth surface.

Deltabeston magnet wire is insulated with asbestos fibre cemented to the wire with a special bond. It is claimed that the maximum continuous working temperature is 150 deg. cent.; for short periods, 260 deg. cent. The insulation thickness is about the same as double cotton and breaks down at 300 to 600 volts.

302. Tapes. Insulating tapes are chiefly of four varieties: (a) those woven from cotton or silk and untreated; (b) those woven from cotton and treated with insulating varnish, or cut from treated cloth; (c) those cut from cloth which has been loaded with rubber or adhesive compound. The lay of the threads is arranged in three different ways, straight, biased and webbed; the last one is the strongest and does not stretch readily. (d) Paper tapes, treated and untreated, are cut from finished stock. See "Specifications and Tests for Insulating Tapes," *Electrical World*, Vol. LVII, p. 488; also Vol. LVI, p. 689.

303. Untreated tapes are hygroscopic and for that reason are not entirely satisfactory unless finally impregnated or protected from moisture. Gray states that a half-lapped layer of untreated cotton tape 6 mils thick will withstand about 250 volts when dry; about 1,000 volts when impregnated. Precautions should be taken to detect the presence of bleaching and chemical matter, such as chlorine, which may attack copper. Webbing is sometimes used for mechanical protection, aside from its insulating qualities.

304. Varnish-treated tapes are cut from sheets of treated cloth, such as Empire cloth, varnished cambric and the like, and are used for taping windings which cannot readily be impregnated. They are cut straight or on the bias, the latter being sometimes preferred for taping uneven surfaces. See treated cloth, Par. **293** to **295**.

305. Rubber-treated tapes are composed of fabric loaded with plastic rubber gum or compound in a soft adhesive state. Such tapes are used extensively in making water-proof joints on underground rubber-insulated cables, or in other locations where a moisture-repellent wrapping is desired. They are frequently used in conjunction with a splicing gum of similar composition, and protected by water-proof insulating compounds and outside wrappings of adhesive tape with insulating paint over all. In the case of underground cables a lead sleeve is wiped over the whole joint, making it completely water-tight.

306. Adhesive or friction tape is composed of fabric loaded with a sticky or adhesive compound. The base of the compound in the more expensive grades is rubber gum, adulterated with fillers in various well-known ways, while the less expensive grades contain little or no rubber and its place is taken by one of the numerous bituminous compounds. This kind of tape possesses fair insulating properties and is very extensively used in low-tension work.

307. Paper tapes of both the treated and the untreated varieties have a most extensive use in the manufacture of paper-insulated cables for power and communication service. See paper, Par. **284.**

308. Asbestos tape, or a tape having a base of asbestos fibre, is superior in its heat-resisting properties to cellulose materials such as paper and cloth. Such tapes are usually known by trade names, among them being deltatape. The latter it is claimed can be raised to 260 deg. cent. before breakdown occurs; puncture voltage, about 250 volts per mil.

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MOLDED COMPOSITIONS

309. Molded insulation embraces a great number of different com positions and compounds, which are difficult of classification. The chie ingredients of some of these materials are well known, while others are mad by secret formulas and processes. Among the raw materials employed i the manufacture of molded materials are mica, asbestos, silica, clay, alkalin earths, wood pulp, cotton, hemp, flax, asphalt, camphor, hydraulic cemen rubber, shellac, copal, dammar gum, rosin, paraffin wax, linseed oil, turper tine, benzine, alcohol, phenol and formaldehyde. The following gener classification of molded materials has been adapted from "Classificatio and Characterization of Molded Insulations," by E. Hemming (*Electric World*, 1914, Vol. LXIII, pp. 761 to 762, 798 to 799, 813 to 817). Th limiting properties given for each class of material below should be con sidered in connection with more specific particulars in the paragraph immediately following.

Class	Allowable temperature (deg. cent.)		Megohms per in-cube*	Dielectric strength (volts per mil)†	Tensile-c strength (lb. pe sq. in.)
	Continuous	Momentary			
Organic, hot-molded...	80	.....	513	143 to 361	940 to 1
Organic, cold-molded...	300	500	380	84 to 167	920 to 1
Inorganic, cold-molded.	900	1,500	900	70 to 72	1,985 to 2
Rubber compounds....	80	100	.....	.....	.....
Organic plastics.....	80	.....	.....	.....	.....
Synthetic resinous products	150 to 250	300	40	42 to 333	2,880 to 5
Molded mica.....	80	175	.....	.....	.....

* Minimum observed value after 72 hr. immersion in water.

† Tests made between blunt needle points; thicknesses of test piece $\frac{1}{16}$ to $\frac{1}{4}$ in.; tested dry.

310. Aetna material is a hard composition employed chiefly for strai insulators. Tests made by Symons (*Jour.* I. E. E., 1904) on a strain insula tor of this material gave the following results: Resistance, 20,000 megohm puncture, 11,000 volts; tensile strength, 5,500 lb.; absorption of water, 3 per cent. of its own weight after 1.5 hr. immersion at 49 deg. cent. Oth tests made on this material gave a dielectric strength of about 90 volts p mil; tensile strength, 1,400 lb. per sq. in. It will withstand great heat, b tends to become brittle at high temperatures.

311. Ambroin (made in Berlin) is a heat-resisting molded material man factured in numerous grades, some of which are claimed to be fireproo while others are suitable for temperature limits of 100 deg. cent. and son for 82 deg. cent. The manufacturers claim that it is moisture-proof, do not shrink, and can be worked and machined. The density ranges fro 1.4 to 1.8, according to quality. Tests made at the Reichanstalt on gra *AF* gave a dielectric strength of 800 volts per mil, in a thickness of 13 mi The tensile strength is about 2,100 lb. per sq. in. and the compressive streng about 2,700 lb. per sq. in.

312. Asbestos-mica comprised of asbestos and mica bound togeth with shellac, is manufactured by the Johns-Manville Co. under the tra name of "molded mica." In appearance it has a dark color and a smoo hard finish. It can be molded into any shape, either with or without met inserts. It softens at about 65. deg cent. and has a safe working temper ture of 55 to 60 deg. cent. The manufacturer gives the dielectric streng as about 335 volts per mil in a thickness of 0.25 in.; tensile strength, 8,5 lb. per sq. in.; but slightly affected by moisture; attacked in some degree acids, depending upon their character and concentration. See *Electri World*, 1912, Vol. LX, pp. 893 and 894.

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313. Asbestos molded with a binder, known under the trade names of gummon, hemit and tegit, is manufactured by the Hemming Mfg. Co., from whom the following data was obtained. Gummon is black and can be highly polished; tegit is dark brown and can be polished, though less highly than gummon; hemit is made in both gray and black and will also take a polish. The density varies, in the neighborhood of 2. These materials are suitable only for molding; are infusible, but will gradually carbonize at higher than working temperatures; will not resist concentrated acid; are not recommended for working pressures above 1,000 volts.

	Ohm-cm. at 22 deg. cent. (Bur. of Stds.)	Max. working temp (deg. cent.)	Dielectric strength (volts per mil)	Strength (lb. per sq. in.)		Absorption of moisture (per cent.)
				Tensile	Compressive	
Hemit.....	1×10^{10}	1,100	50	2,000	1,600	5
Gummon....	3×10^{12}	320	75	600	550	2
Tegit.....	2×10^{12}	200	50	1,200	1,100	5

Also see Hemming, E. "Molded Electrical Insulation and Plastics;" Clausen and Co., New York, 1914.

314. Asbestos wood or lumber, known also by the trade names "Transite Asbestos Wood" and "Asbestos Building Lumber," consists of asbestos fibre and hydraulic cement, and is used as a substitute for wood in building construction. It is also used to some extent as a substitute for slate and marble in electrical construction. The following data (Par. **315** and **316**) was furnished by C. L. Norton; also see his paper entitled, "Some Refractory Substitutes for Wood," *Jour.* A. S. M. E., 1912; and "The Manufacture and Use of Asbestos Wood," on pp. 375 and 379 of "Technology and Industrial Efficiency," McGraw-Hill Book Co., Inc., New York, 1911.

315. Transite asbestos wood is light gray in color and is manufactured in sheets up to about 4 ft. by 8 ft. by 2 in. It has a density of about 2.0. It can be sawed and bored like wood but is harder and slower to cut. At 600 deg. cent., partial dehydration and partial loss of strength occurs, but it does not soften. At 1,100 deg. cent. the material holds shape and considerable portion of its strength, but it will not stand temperatures above 1,400 deg. cent. The temperature coefficient of expansion at ordinary temperatures is about 0.000008 per deg. cent. The thermal conductivity is 0.0005 cal. per cm-cube per sec. per deg. cent. Transverse breaking tests give a modulus of rupture of about 5,000 lb. per sq. in., and the crushing strength is from 20,000 to 25,000 lb. per sq. in. When dry, at or near 20 deg. cent., it has a resistivity of about 150,000 megohm-cm. It is dissolved slowly by acids. When used in dry or hot places it is suitable for electrical insulation and is tougher than slate or marble. Since it absorbs moisture it is not suitable for damp locations.

316. Ebony asbestos wood is asbestos bonded with magnesia, cement and saturated with an insulating compound. It is black, smooth and glossy and has a density of about 1.9. It can be worked the same as slate, but more rapidly and easily. The working temperature limit is about 200 deg. cent.; it does not soften; the melting-point is above 1,400 deg. cent. The coefficient of expansion is 0.000010 per deg. cent. The thermal conductivity is 0.00065 cal. per cm-cube per sec. per deg. cent. It has a modulus of rupture of about 5,000 lb. per sq. in. and a crushing strength of 15,000 lb. per sq. in. At 20 deg. cent. after 96 hr. immersion the resistivity is above 3×10^6 megohm-cm. and changes 5.3 per cent. per deg. cent. The disruptive strength is greater than that of slate or marble, and it also withstands better the effects of surface arcing. It is also tougher than slate or marble.

317. Bakelite and bakelite compositions. Bakelite is a condensation product of phenol, manufactured in three grades. Bakelite "A" is the initial raw material and exists in liquid, pasty or solid condition; upon heating it is converted into "B" which is an intermediate solid product,

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softening under application of heat and suitable for molding; bakelite "C" is the final product, produced by heating "A" or "B," and is a hard, non-resinous, infusible solid, in appearance resembling amber or hard rubber. In color it can be made transparent or opaque; colorless to yellow, brown, red and black. The coloring matter, when any is used, consists of organic dyes or mineral pigments. The raw material is sold in dissolved, liquid or solid condition, and is used for varnish, lacquer, enamel, impregnation, adhesive cement, plastic molding compositions and molded articles. It can be molded into any shape by casting or by forming in the hot press, and will receive metal inserts. In condition of final hardness it can be worked, machined and polished like amber or hard rubber, and can be used at continuous temperatures considerably above 100 deg. cent. It is not a good conductor of heat. For short periods it will stand 250 to 300 deg. cent. Swoboda gives 230 deg. cent. as the maximum working temperature of bakelite-asbestos. At higher temperatures it is infusible, but chars. It is not attacked by the solvents or many of the acids, but will not withstand hot sulphuric acid, nitric acid, bromine or strong alkaline solutions; the effect of chemicals is dependent in some degree upon the grade of material. It is non-hygroscopic, and is said to resist steam and boiling water. The data given below were furnished by Dr. L. H. Baekeland, the inventor of bakelite.

	Density	Dielectric strength (volts per mil)	Strength, (lb. per sq. in.)		Coef. of expansion per deg. cent.
			Tensile	Compressive	
Bakelite "C"	1.26	560	5,000	26,000	0.00011
Baked film of bakelite varnish No. 2	.....	2,500	.....	.....	.....
Bakelite-wood fibre	1.34	530	4,200	27,000	0.000034
Bakelite-asbestos	1.90	200	4,200	24,000	0.000023
Bakelite-micarta (sheet)	.....	950 to 1,120	16,500	.....	.....
Bakelite-dielecto (sheet)	.....	635 to 1,130	.....	.....	.....

Resistivity of "C" at 26 deg. cent., 5×10^{11} to 3×10^{12} ohm-cm.; dielectric constant, 4.1 to 8.8. The resistivity and the dielectric strength decrease at temperatures above 75 deg. cent. For further data on bakelite see: *Journal of Ind. and Eng. Chem.*, 1909, Vol. I, No. 3 and No. 8; 1911, Vol. III, No. and No. 12; 1912. Vol. IV, No. 10; 1913, Vol. V, No. 6. *Trans.* A. E. S., 190 Vol. XV. *Elec. World*, 1911, Vol. LVII, pp. 632 to 634. *Met. and Chem. Eng.*, Jan. 1912. *Jour. Soc. Chem. Industry*, June 16, 1913, Vol. XXXII.

318. Celluloid, formerly known as xylonite, is composed essentially of soluble guncotton (pyrolin) and oil (camphor). In texture and color it resembles ivory, and is variously colored in imitation of amber, coral, tortoise shell, etc. It is very slightly hygroscopic and can be molded in any form by softening in boiling water. It is highly inflammable. The density is 1.44. The resistivity at ordinary temperatures is from 2×10^{9} to 8×10^{10} ohm-cm. According to Thomas (*Jour. Franklin Institute*, 191 Vol. CLXXVI, pp. 283 to 301), celluloid tested at 1,000 cycles has effective resistivity of 2×10^{9} ohm-cm. and a dielectric constant of 13. Clear celluloid has a dielectric strength of 250 to 700 volts per mil at deg. cent., and 100 to 300 volts per mil at 100 deg. cent.; colored samples 250 to 470 volts per mil (Turner and Hobart). Thomas gives a puncture voltage of 1880 volts per mil, at 1,000 cycles. At 920 cycles the effective resistance is 28×10^{9} ohm-cm.; dielectric constant, 4.02; power-factor, 0.0 (Fleming and Dyke).

319. Condensite is a molding material of which the chief constituent is a compound resulting from chemical reaction between phenol and formaldehyde, classed as a phenolic condensation product. It can be prepared in many forms, transparent or translucent, in a variety of colors; it is adapted as molding material, varnish, enamel, impregnating material and cement. The first step in its manufacture is the production of a resinous gum-l

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substance which will not harden under heat; this product is heated and then combined with a hardening agent, producing a hard, infusible and practically insoluble substance which the manufacturer (Condensite Co. of America) claims is high in dielectric and mechanical strength and heat resistance. The following data on the properties of molded condensite were furnished by the manufacturer: Density, 1.25 to 2.0; not hygroscopic, unaffected by water, insoluble in the ordinary solvents and oils, attacked by strong nitric acid and caustic potash, slightly attacked by sulphuric acid. The resistivity at 22 deg cent. is about 4×10^{16} ohm-cm. (Bur. of Stds.); dielectric strength, about 300 to 400 volts per mil at a thickness of 0.15 in. and 500 to 600 volts per mil at a thickness of 0.04 in.; tensile strength, 4,300 lb. per sq. in.; compressive strength, 26,000 lb. per sq. in.; not perceptibly affected by 48 hr. of exposure to a temperature of 200 deg. cent.; maximum working temperature, 300 deg. cent. (Swoboda, *Elec. Jour.*, May, 1913).' Also see *Electrical Review and West Elec.*, Vol. LX, p. 199.

320. Dielectrite is a black molded composition composed of vegetable fibre and mineral filler. It is molded and vulcanized by the application of heat. Resistivity at 22 deg. cent., 5×10^{12} ohm-cm.

321. Electrose is a dark brown or black composition of hard, tough quality which it is claimed is non-hygroscopic and not affected by water or oil. It can be molded in any form, will hold metal inserts, and can be given a smooth glossy finish. The working temperature limit is about 95 deg. cent. Resistivity at 22 deg. cent., 1×10^{14} to 200×10^{14} ohm-cm. The manufacturer (Electrose Mfg. Co.) claims a dielectric strength of at least 600 volts per mil, in a thickness of $\frac{1}{4}$ in. Electrose is used in the manufacture of many different forms of insulators and bushings and is also made in pliable insulating flooring. See *Electrical World*, Vol. LIV, p. 797 and Vol. LVI, p. 887.

322. Gohmak is a molded substitute for hard rubber made by the Vulcanised Products Co. The density ranges from 1.4 to 1.8 according to composition. The claim is made that it is non-hygroscopic and insoluble in oils and weak solutions. Resistivity, on the order of 2×10^{16} ohm-cm. at ordinary temperatures, decreasing with rising temperature. Dielectric strength, on the order of 400 volts per mil, at a thickness of 0.25 in. Tensile strength, 9,000 to 12,000 lb. per sq. in. Softens slightly at 100 deg. cent.

323. Insulate is a black molded composition composed of mineral compound and resembles hard rubber. It can be moulded in any shape and can be worked and machined. The manufacturers (General Insulate Co.) claim that it is non-hygroscopic, insoluble in all weak solutions and has a maximum working temperature of 150 deg. fahr. The resistivity of No. 2 grade at 22 deg. cent. is 8×10^{15} ohm-cm. The dielectric strength is on the order of 45 volts per mil, at a thickness of 0.4 in.

324. Molded mica is made of finely split mica scales held together by a strong insulating varnish, binder, or cement, such as shellac, the sheets or forms thus built up being subjected to heat and pressure. These compositions are more or less heat resisting, dependent upon the nature and proportions of the binder employed. They are known by a variety of trade names such as micanite, mica plate, micabond, micabeston, turbomic, formica, megomit, megotalc, etc. The less binding material they contain, the nearer they approach the properties of natural mica. Such reconstructed or molded mica is made in three commercial forms, as follows: (1) Molded plate, which becomes flexible when heated and in that condition can readily be formed into various shapes such as rings, troughs, spools, and, in thinner sheets, rolled into tubes. Upon cooling it regains its rigidity. It can be used for any purpose where very high temperatures are not encountered, except for commutator bars. (2) For insulating commutator segments. It cannot be molded and offers great resistance to heat. Canadian amber mica is preferred for this purpose. (3) Flexible sheets which may be bent to shape without application of heat, for insulating armature slots, magnet and commutator cores, etc. It is also used in conjunction with tapes for insulating wires and cables.

Rayner concluded from his tests (National Physical Laboratory) that generally speaking, thin qualities of micanite up to about 1 mm. will withstand a stress of 20,000 volts per mm. (500 volts per mil) in air for 10 min. Above this thickness, up to 2.5 mm., there is more difficulty in making material which will withstand this stress, and usually the material withstands the voltage longer under oil.

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The Mica Insulator Co. gives the following dielectric strengths for micanite of different grades:

Use	Grade	Thickness (mils)	Volts per mil
For molding	India	10. to 125.	955
For commutators	India	10. to 125.	955
For molding	Amber	20. to 62.5	830
Plate for flat work	India	62.5 to 500.	800
Flexible	India	5. to 125.	588

The resistivity is on the order of 10^{15} ohm-cm.

325. Roxite is a black moulded composition, the properties of which are given as follows by the Northern Industrial Chemical Co. Density, 1.8; can be molded into any shape and will receive metal inserts; will take a high polish; infusible and insoluble; will not support combustion; absorbs 0.5 to 1 per cent. of water after 24 hr. immersion; dielectric strength, 80 volts per mil.

326. Sternoid (Dickinson Mfg. Co.) is a black, heat-resisting, molded material which the manufacturers claim has high dielectric and tensile strength and is heat-proof up to 260 deg. cent. The same manufacturer also produce other molded materials known as **stern-asbeston**, heat-proof up to 200 deg. cent.; **stern-condensite**, heat-proof up to 175 deg. cent and capable of being worked, machined and polished; rubber-substitutes heat-proof up to 70 deg. cent.

327. Vulcabeston (Johns-Manville Co.) is an insulating material made of **asbestos and rubber**, the latter being used as a binder. This material is grayish brown in appearance, can be molded into nearly any shape, and has a surface which will not take a smooth finish. The softening point is about 175 deg. cent., with a safe working temperature of about 150 deg cent. The resistivity at 22 deg. cent. is about 2×10^{10} ohm-cm. The dielectric strength is about 90 volts per mil, the test pieces being 0.25 in thick. Change in temperature has no effect on the dielectric strength Since this material is of a fibrous nature, it is not suitable for use in dam places. Acids have a slight effect upon it. The transverse strength 3,600 lb. per sq. in. See *Electrical World*, 1912, Vol. LX, pp. 893 and 894

328. Vulcabeston No. 201 (Johns-Manville Co.) is a material composed of **asbestos and a special gum** used as a binder. In appearance it has a brown mottled surface which will take a very high finish. Intricate and complicated pieces can be readily molded from it, using metal inserts desired. The softening temperature is between 260 and 300 deg. cent and the safe working temperature is about 230 deg. cent. The dielectric strength is about 115 volts per mil with test pieces 0.25 in. thick. Transverse strength, 9,000 lb. per sq. in. Not affected by most acids, and not affected by oil or water.

329. Vulcalose is a molded material having the properties of hard rubber except that it is said to be considerably tougher. It can be molded in any form and is used, among other purposes, for insulators.

RUBBER AND ITS DERIVATIVES

330. Rubber or caoutchouc is the general name applied to a great number of different natural gums, the different varieties being of decided unlike characteristics, but having among themselves certain common properties and similar constituents. The synthesis of rubber shows that it belongs with the terpenes, having the formula $(C_{10}H_{16})_n$, but thus far all attempts to show the size of the molecule have been unsuccessful. In addition some of the crude rubbers contain proteids, resins, hydrocarbons, etc in some cases it requires extensive treatment to obtain the pure gum. Crude rubber is obtained by coagulating and drying the milky latex obtained from certain species of trees and plants, the principal sources being in South America, Central America, Africa and Asia, the Amazon district of South America being especially noted for its high-grade rubber. Crude rubber affected in marked degree by temperature, being soft and sticky when warm but stiff when cold.

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331. Reduction of crude rubber. The lumps or biscuits of crude rubber are boiled in water, ground, washed, dried, mixed with sulphur, adulterants and filler and then calendered. For details of the process see Perrine, F. A. C. "Conductors for Electrical Distribution," New York, 1903; and Esch, W. "Handbook for India-rubber Engineers," Hamburg, 1912. Owing to the high cost of pure rubber it is almost universally adulterated and many rubber products do not contain over 20 to 30 per cent. of pure gum, and sometimes much less. Among the numerous adulterants in use are rubber substitutes, ozokerite, paraffin, pitch, oil, etc., and fillers such as zinc oxide, white lead, red lead, barium sulphate, magnesium carbonate, barium carbonate, chalk, lamp-black, talc, alumin flakes, etc.

Vulcanization. When rubber and sulphur are heated to a temperature above the melting-point of the latter, 120 deg. cent., the two combine and form a new product termed vulcanized rubber, which is stronger, more elastic and less susceptible to temperature changes than pure rubber. The degree of vulcanisation depends upon the proportion of sulphur, the temperature and the duration of heating.

332. Rubber substitutes in the true sense have not yet been produced on a commercial scale. There are certain so-called substitutes, produced from vegetable oils by processes of vulcanization or oxidation, which can advantageously be mixed with rubber for the production of certain articles. Rubber substitutes used not infrequently in wire insulation consist principally of oxidized oils, paraffin, resins and rubber shoddy. The latter is a compound obtained by treating old rubber with steam, sulphuric acid and chloride of zinc, thus removing most of the vegetable fibres and the sulphur, but leaving the mechanical admixtures of earth and oxides employed in the original manufacturing process. Such substitutes are usually known under trade names.

333. Electrical properties. The resistivity is on the order of 10^{14} to 10^{16} ohm-cm., varying greatly according to the composition and increasing with the content of pure rubber. The temperature coefficient is negative and unusually large, ranging from 2 to 4 per cent. per deg. cent. Del Mar states that at any given temperature the rate of change of resistance per deg. of temperature change is approximately proportional to the resistance at that temperature, values of the factor ranging from 0.02 to 0.03 for 30 per cent. Para compound. Values of k in the formula $R = k \log_{10}(D/d)$ for insulation resistance of cylindrical wires in megohm-miles, are variable between wide limits, ranging from about 1,000 to 20,000; d is the diameter of the wire and D is the outer diameter of the insulation, in the same units. The value of k is very much higher with alternating currents.

The dielectric constant of pure vulcanised rubber is from 2 to 3; rubber compounds, 3 to 4. Jona gives values as high as 6 for certain compounds containing relatively large percentages of Para.

The dielectric strength of high-grade rubber compound ranges from 300 to 500 volts per mil; it decreases quite appreciably for long periods of electrification. Lufkin states (*Electrical World*, 1913, Vol. LXI, p. 1310) that for each rubber compound there is a critical temperature at which the puncture voltage is a maximum. This ranged between 40 deg. and 80 deg. cent. for five different grades, in a certain series of tests. One particular grade, or high quality, gave a maximum at 70 deg. cent., being 30 per cent. above the value at 20 deg. The range was carried to 100 deg. cent. at the upper limit, and 0 deg. at the lower.

Fleming and Dyke measured the power-factor of rubber at 920 cycles and found values of 0.005 for pure India-rubber and 0.002 for vulcanized India-rubber. For further data on electrical properties, consult the following:

Jona, E. "Insulating Materials in High-tension Cables;" *Trans.* Int. Elec. Congress, St. Louis, 1904, Vol. II, pp. 550 to 571.

Fisher, H. W. "Rubber-covered Wires;" *Trans.* A. I. E. E., 1907, Vol. XXVI, pp. 997 to 1025.

Osborne, H. S. "Potential Stresses in Dielectrics;" *Trans.* A. I. E. E., 1910, Vol. XXIX, pp. 1553 to 1581.

Hering, C. "Thickness of Electric and Thermal Insulation," *Electrical World*, 1911, Vol. LVIII, pp. 1303 to 1305.

Lendi, J. H. "The Thickness of Insulation on Wires and Cables," *Electrical World*, 1912, Vol. LIX, pp. 590 to 592.

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334. Mechanical properties.* The density of pure rubber is 0.93 t 0.97; rubber compounds, 1.7 to 2.0. A properly vulcanized compound c high-grade rubber suitable for the best hose and packing, has a tensi strength of about 2,000 lb. per sq. in. and may be stretched to about seve times its original length. The physical properties, however, are subjec to wide variations depending upon the relative proportions of gum and fill and the extent of vulcanization. The real value of rubber depends upo the length of time which it will retain its desirable properties. It ofte deteriorates less rapidly when in use than when lying idle; deterioration accelerated by heat and especially by sunlight, probably as the result c oxidation. Other things being equal, the better grades are stronger, mo elastic and more durable than the poorer grades.

The following tests made by the Bureau of Standards indicate the prope ties of six different grades of rubber (See Circular No. 38).

Sample	Tensile strength (lb. per sq. in.)		Ultimate elongation (per cent.)		Set† (per cent.)	
	Longi-tudinal	Trans-verse	Longi-tudinal	Trans-verse	Longi-tudinal	Trans-verse
1	2,730	2,575	630	640	11.2	7.3
2	2,070	2,030	640	670	6.0	5.0
3	1,200	1,260	480	555	22.1	16.3
4	1,850	1,700	410	460	34.0	24.0
5	690	510	320	280	27.5	25.0
6	880	690	315	315	34.3	25.9

† After 300 per cent. elongation for 1 min., with 1 min. rest. The set an the tensile strength were determined on different test pieces.

335. The safe working temperature limit for cables insulated wit rubber gum or rubber compounds is 50 deg. cent.

336. Chemical activity. Rubber compounds containing sulphur a injurious to copper. Rubber-covered copper wires should be protected b a coating of tin. Rubber is attacked by oil and therefore rubber-covere conductors should never be immersed in insulating oils, which applies t any form of rubber insulation.

337. Specifications and tests for 30 per cent. Hevea rubber-insulatin compound were prepared in 1914 by a joint rubber insulation committe appointed by a group of manufacturers and users of rubber compound The full report and specifications will be found in the *Proc.* A. I. E. E., Jan 1914, pp. 121 to 140. Specifications for rubber-insulated wire have bee prepared by a number of associations; see R. S. A. "Manual."

338. Chatterton's compound is composed of 3 parts gutta-percha, part rosin and 1 part Stockholm tar. It is used for filling the interstic between the strands of cable conductors before applying gutta-percha, i submarine cables.

339. Clark's compound consists of 60 parts mineral pitch and 40 par of finely ground sand. It is employed to impregnate jute yarn wrapping c the outside of armored submarine cables.

340. Gutta-percha is a natural gum, the best quality of which is obtain from the Isonda gutta-tree found in Sumatra, Borneo and Malacca. gum known as **Ballata**, which is quite similar to gutta-percha, is found i Venezuela. The density of gutta percha is 0.97 to 0.98 and its properti are generally the same as those of pure rubber. Crude gutta-percha is r duced in the same manner as crude rubber, but unlike the latter it is used i the pure state, principally for submarine cable insulation. Fleming an Dyke found that at 920 cycles the effective resistivity is 34×10^9 ohm-cm apparent dielectric constant, 2.86; power-factor, 0.020. For extended info mation on gutta-percha and its properties see Clouth, F., "Rubber, Gutt

* The Testing of Mechanical Rubber Goods; Circular No. 38, U. S. Bures of Standards; 1913. Also see "Reports of Tests of Metals" (Watertow Arsenal), Gov. Printing Office, Wash., D. C., 1909.

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percha and Balata," Cologne, 1903; Seeligmann, Torrilhon and Falcounet, "India-rubber and Gutta Percha," 1910; Del Mar, W. A., "Electric Power Conductors," 2d edition, New York, 1914; Kempe, H. R., "A Handbook of Electrical Testing," 7th edition, London, 1908.

341. Hard rubber or ebonite is a rubber compound containing a large percentage of sulphur and highly vulcanised. It is a hard dense material possessing many desirable properties as an insulator at temperatures not greatly exceeding normal. The resistivity is on the order of 10^{15} to 10^{16} ohm-cm. at ordinary temperatures; the surface resistivity is impaired by exposure to sunlight (See Scientific Paper No. 234, Bureau of Standards.) The dielectric constant is from 1.9 to 3.5. In small thicknesses, of 20 mils, the dielectric strength ranges from 1,700 to 3,750 volts per mil, tested between 1-in. spheres; 1,000 to 2,000 volts per mil, tested between flat electrodes. At 920 cycles it has an effective resistivity of about 1.5×10^{11} ohm-cm.; dielectric constant, 3.17; power-factor 0.005 (Fleming and Dyke). Mechanically it is brittle, but can be worked, machined and polished; tensile strength, about 1,100 lb. per sq. in. and compressive strength about double; density, 1.2 to 1.25. It is attacked by oils and osone, but is non-hygroscopic. See Farmer, F. M., "The Dielectric Strength of Thin Insulating Materials," *Trans.* A. I. E. E., 1913, Vol. XXXII, pp. 2097 to 2131; also Paterson, Rayner and Kinnes, "Notes on the Testing of Ebonite for Electrical Purposes," *Jour.* I. E. E., 1913, Part 217, Vol. L.

342. Kerite is a vulcanised compound of oxidised linseed oil and rubber combined with various vegetable oils, invented by A. G. Day. According to Perrine* it has a specific insulation resistance somewhat less than pure rubber, but is said to be mechanically more durable than any insulation manufactured from pure rubber. It is employed in the insulation of wires and cables as a substitute for the usual rubber compound. The value of the constant k in the formula $R = k \log_{10} (D/d)$ is given by the Kerite Ins. Wire and Cable Co. as 4,000 at 60 deg. fahr.; R is the insulation resistance of the wire in megohm-miles, d is the diameter of the conductor and D is the outside diameter of the insulation.

343. Sulphur has a resistivity of 10^{17} ohm-cm. at 22 deg. cent.; dielectric constant, 2.2 to 3.9; power-factor at 920 cycles, 0.0003.

344. Vulcanite. See hard rubber, Par. 341.

VARNISHES AND COMPOUNDS

345. Solidifying materials, such as varnishes, which are applied as liquids and emerge as solids, are of interest chiefly in their final state. They are divisible broadly into two classes: (1) those employed to impregnate or treat basic materials, such as the fibres and the pulps; (2) those employed as filling compounds, to permeate or seal extensive voids which otherwise would offer lodgment for moisture and deleterious foreign matter. The properties of the former class are obviously of importance, principally, in association with the treated or impregnated base; while materials of the latter class constitute a species to themselves.

346. Insulating varnishes are divisible, according to their applications, into four groups:† (A) For impregnating windings; (B) for treating papers and fabrics; (C) for cementing purposes; (D) finishing varnishes. They are also divisible, according to their properties, into (a) oxidising and (b) non-oxidising, and again into (1) air-drying and (2) baking. Oxidising varnishes of class A are frequently composed of linseed oil with a resinous base of copal or other fossil gum, and when thoroughly oxidised are almost impervious to oil and moisture. The drying action in linseed-oil varnishes takes place first by the evaporation of the volatile solvent and then by the oxidation of the oil and the gum; the latter action is hastened by the addition of mineral driers, the quantity of which depends upon whether air-drying or baking varnish is desired. In another form of oxidising varnish the gum base is replaced by asphaltum, but this is said to lower the dielectric strength and the resistance to attack by oil. Non-oxidising varnishes of class A contain a

*Perrine, F. A. C. "Conductors for Electrical Distribution," New York D. Van Nostrand Co., 1903, p. 106.

†See Fleming and Johnson. "Insulation and Design of Electrical Windings;" Longmans, Green and Co., London, 1913; pp. 63 to 76.

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base of gum or asphaltum with a spirit solvent, shellac varnish being a example. Varnishes of class B are composed in some instances of linseed o with a gum base, and a mineral drier such as manganese borate or litharg in other cases linseed oil alone is used. It is essential that varnishes c class A and class B should be as nearly as possible impervious to moistur and, for oil-immersed apparatus, not attacked by transformer oil. In th varnishes of class C, shellac is probably the most extensively employe Class D varnishes are used mainly for the sake of appearance and to provid a hard smooth exterior surface in the interest of cleanliness.

347. Impregnating, filling and sealing compounds are prepared fro a multitude of different formulas. In most instances their composition guarded as a manufacturing secret and they are marketed under various trad names, such as Ajax, Armalac, Benolite, Insulatine, Insulac, Ohmlac, Oxit Resistolac, S. V. W., Victolac, Voltalac, etc. Impregnating varnishes hav been superseded to some extent by compounds having an asphaltum or pa affin base dissolved in thinning material, which are chemically more iner more resistant to moisture, better heat conductors and capable of filling th interstices of windings. Their use is chiefly limited by their temperatu characteristics. The compounds on the market offer a fairly wide range choice in temperature characteristics, the softening or flow points varyin from about 50 to 130 deg. cent. The Minerallac Elec. Co. gives the followin properties for Minerallac No. 2, a semi-solid compound: softening point, deg cent.; melting-point, 63 deg.; flash-point, 202 deg.; burning-point, 21 deg.; resistivity, 1.3×10^{15} ohm-cm.; dielectric constant, 2.1; dielectri strength, 1,000 volts per mil.

In the case of filling and sealing compounds, the thermal properties a relatively of more importance than the dielectric strength; chemical inertne and imperviousness to moisture are very important. These compoun should be tested for softening point, evaporation, melting or pouring poin flash-point, burning-point, characteristics at extremes of working temper ture, cubical expansion, chemical activity, effect of moisture and electric properties.

348. Vacuum drying and impregnation is very extensively employe in the application of fluid or liquid treating materials. The winding substance to be impregnated is first dried in a steam-heated, vacuum chambe then the hot insulating fluid is admitted, the vacuum is let down, and pressu is applied, to the extent sometimes of 50 lb. per sq. in. In this way the moi ture is driven out and the maximum degree of impregnation is secured.

349. Asphalt is a natural mineral pitch of bituminous character em ployed in the manufacture of insulating varnishes and impregnating com pounds. Chemically it is a mixture of hydrocarbons, generally black color, hard at ordinary temperatures, becomes viscous at about 70 deg. cen and melts at about 100 deg. cent. The density is from 1.04 to 1.40. It more or less soluble in oil of turpentine, ether, alcohol and chloroform. Th dielectric constant is about 2.7 and the dielectric strength according Symons is 30 volts per mil at a thickness of $\frac{1}{4}$ in.

350. Bitumen. The term originally referred only to asphalt or **miner pitch**, but its meaning is now extended to embrace any of a number of inflam mable mineral substances consisting mainly of hydrocarbons, and includi also the mineral **tars**. Coal-tar pitch is a fair insulator, but is britt according to Symons it has a dielectric strength of about 50 volts per mil.

351. Enamel (baked) insulation for small magnet wires has to great extent displaced cotton and silk, or is used in conjunction with the The composition of the enamelling compounds used by different man facturers is guarded with much secrecy; the base of the compound, in som instances, is said to be **stearin pitch.** Chemically stearin is glyceryl tri tearate; it melts at 67 deg. cent. It is also known as tristearin and is prominent constituent of many animal and vegetable fats and oils.

The wires are drawn slowly through a warm bath of the melted compou and then through a baking oven, the process being repeated to secure many coatings as required. One of the defects sometimes found in the co ing is the occurrence of very small holes, like pin holes, exposing the condu tor; such defects can be detected by drawing the wire through a mercu bath. The coating is usually very thin, on the order of a few tenths of a m The dielectric strength varies over a range of about 300 to 1,200 volts (ma

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per mil, an average value being 500 to 600 volts per mil, or about four times the value for silk. The electrical resistivity at ordinary temperatures is very high, on the order of 10^{16} ohm-cm. Baked enamel should stand a temperature of 100 deg. cent. continuously without injury, but breaks down electrically at about 300 deg. cent. It is a fairly good thermal conductor and much superior to cotton and silk. An enameled wire should withstand winding around a mandrel four times its own diameter without injury. Turpentine, shellac, alcohol, vegetable or animal oils, and coal-tar solvents will attack it, but it is not injured by clean mineral oil and is moisture-proof. It should be carefully handled to avoid injuring the coating.

351. Linseed oil is a vegetable material derived from flaxseed, having a density of 0.932 to 0.936 at 15 deg. cent. It has excellent insulating properties and is extensively used in paints and varnishes. For specifications and general properties see "A. S. T. M. Standards;" and Technologic Paper No. 9, Bureau of Standards, 1912. Boiled linseed oil has the property of oxidizing under ordinary exposure to air and the process will continue until it becomes viscous or even hard; the action can be hastened by drying agents and the application of heat.

352. Ozokerite (ozocerite) is a wax-like mineral, colorless or white when pure and consisting of a mixture of hydrocarbons. It is used in making cerecan, candles, etc. Crude ozokerite has a resistivity on the order of 4.5×10^{14} ohm-cm. Liquid ozokerite has a dielectric constant of about 2.1. **Ceresin** is a yellow or white wax made by bleaching and purifying ozokerite and is employed as a constituent of insulating compounds; its density is 0.75; resistivity, over 5×10^{15} ohm-cm. at 22 deg. cent.

354. Paraffin is a colorless or white waxy substance, consisting of a complex mixture of hydrocarbons, obtained by the distillation of wood, coal or oil. Chemically it is inert, being unaffected by most strong reagents. According to composition, it melts at from 45 to 80 deg. cent. and has a density of 0.87 to 0.94; resistivity, 10^{15} to 10^{19} ohm-cm.; dielectric constant, 1.9 to 2.3; dielectric strength, about 300 volts per mil; power-factor at 920 cycles, 0.0003.

355. Resin is defined as any of various solid or semi-solid organic substances, chiefly of vegetable origin, usually yellowish to brown in color, transparent or translucent, and soluble in ether, alcohol, etc., but not in water. They soften and melt on heating. Chemically they differ widely, but all are rich in carbon and hydrogen and contain also some oxygen. Among the commercial resins are amber, copal, dammar, guaiacum, lac, mastic, rosin and sandarac. Lac is the raw material used in making **shellac**, which has a resistivity on the order of 10^{15} to 10^{16} ohm-cm. and a dielectric constant of about 2.7 to 3.8.

356. Wax is defined as any of a class of natural substances composed of carbon, hydrogen and oxygen and consisting chiefly of esters other than those of glycerin or of free fatty acids. In this class are included beeswax, spermaceti, Chinese wax, carnauba wax, etc. Beeswax is a dull yellow solid, of density 0.96 to 0.97 at 15 deg. cent. and melting at 62 to 64 deg. cent.; resistivity, 10^{14} to 10^{17} ohm-cm.; dielectric strength, about 250 volts per mil.

357. Weatherproof compounds for saturating the cotton braids on weatherproof wire usually contain an asphaltum base, with an admixture of wax so that the surface of the braid may be given a dull polish.

INSULATING OILS

358. Oil is employed as an insulating medium in many ways. It is employed by itself to insulate transformers and switches by immersion; it is used for saturating fibrous and other materials, as in cable work; drying oils (linseed) are used for coating papers and cloths in sheet insulation; various kinds of oil are employed in mixing insulating paints and varnishes. Oils of practically every variety are possessed of very high resistivity and dielectric strength. Chemically oil is composed of hydrocarbons having the general formulas C_nH_{2n+2} and C_nH_{2n}. The desired characteristics of an insulating oil are high resistivity and dielectric strength, low viscosity, high flash point, chemical neutrality toward metals and insulating materials, freedom from moisture, sediment and impurities, and chemical stability under local high temperatures.

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359. Transformer oil. The ideal cooling and insulating fluid for a transformer should have the characteristics named in Sec. 6, Par. 60. The oil largely used is a mineral oil obtained from crude petroleum by fractional distillation, having the following characteristics.

	Medium	Light
Flash point, deg. cent.	180 to 190	130 to 140
Burning point, deg. cent.	205 to 215	140 to 150
Cold test	−10 to −15	−15 to −20
Density at 13.5 deg. cent.	0.865 to 0.870	0.845 to 0.850
Viscosity at 40 deg. cent. (Saybolt test).	100 to 110 sec.	40 to 50 sec.
Acid, alkali, sulphur, moisture	None	None

When free from moisture the dielectric strength, between 0.5-in. discs 0.5 in. apart, with sine-wave e.m.f., should be from 45,000 to 50,000 volts; or between 0.5-in. brass spheres 0.15 in. apart the average dry oil should not break down at less than 30,000 volts. The medium grade of oil is usually employed in self-cooled apparatus and the light grade in water-cooled apparatus, but the dielectric strengths are the same. The dielectric strength between 0 and 100 deg. cent. increases about 0.4 to 0.5 per cent. per deg. The resistivity of dry oil is on the order of 10^{12} ohm-cm. and decreases with rise of temperature. The effect of moisture is very harmful (Par. 361) and it is of the greatest importance to keep oil absolutely dry or as nearly so as possible. One of the principal advantages of oil as an insulator is its property of self-restoration after dielectric discharge or puncture; this property is not independent, however, of the energy of discharge, and excessive energy may overheat the oil and cause explosion or fire. The specific heat of transformer oil is about 0.39 to 0.51 and the thermal conductivity ranges from 0.00033 to 0.00043 gram-calorie per cm-cube per deg. cent. per sec. The following references should be consulted for further information.

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360. Electrical properties of oil

(Circular No. 36, U. S. Bureau of Standards, p. 24)

Oil	Density at 20 deg. cent.	Resistivity (ohm-cm.)	Phase difference		Dielectric constant
			100 cycles	1,200 cycles	
Pratts astral (kerosene).	0.7852	470×10^{12}	0°2′11″	0°0′25″	2.34
Paraffin	0.8710	$1{,}100\times10^{12}$	0°0′35″	0°0′ 5″	2.41
Transformer oil (A)	0.8795	0.49×10^{12}	1° 5′0″	0°5′10″	2.51
Transformer oil (B)	0.8682	3.1×10^{12}	0°30′0″	0°5′30″	2.47

361. Dielectric strength of oil with a 1-mm. gap (39.4 mils), expressed in volts per mm., is given in the table below for numerous varieties of oil.

Castor	13,000	Neatsfoot	9,000
Cottonseed	7,000	Olive	7,500
Lard	4,000	Paraffin	16,000
Linseed, raw	9.000	Sperm, mineral	8,500
Linseed, boiled	8,000	Sperm, natural	9,000
Lubricating	5,000	Turpentine	11,000

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The specifications for breakdown voltage with the three different types of spark gap most widely used are as follows:

1.0-in. disks spaced 0.1 in. apart, breakdown 22,000 volts
0.5-in. disks spaced 0.2 in. apart, breakdown 38,500 volts
0.5-in. spheres spaced 0.15 in. apart, breakdown 40,000 volts

362. Dielectric constants of various kinds of oils are given in the accompanying table. The values probably change very appreciably with the temperature.

Arachid	3.17	Petroleum	2.02 to 2.19
Castor	4.6 to 4.8	Rape seed	2.2 to 3.0
Colza	3.07 to 3.14	Sesame	3.17
Lemon	2.25	Sperm	3.02 to 3.09
Neatsfoot	3.07	Turpentine	2.15 to 2.28
Olive	3.08 to 3.16	Vaseline	2.17

363. Effects of moisture and dust on insulating properties of oil. The presence of moisture in transformer oil has a very serious effect on the dielectric strength, as shown by Fig. 36. In order to obtain a dielectric strength of 40,000 volts (0.2-in. gap between 0.5-in. discs), the water present as distributed moisture in the oil must not exceed 0.001 per cent. Fine dust is also very injurious to the dielectric strength. For these reasons, various manufacturers have developed oil dryers and purifiers, which operate on the principle of a filter press.

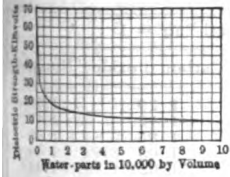


Fig. 36.—Effect of water on dielectric strength of oil.

364. Formation of deposits in oil-cooled transformers. The foregoing subject formed the title of a paper by Dr. A. C. Michie before the I. E. E. in April, 1913. The author stated that all oils oxidize in time, but the formation of deposits can be prevented or minimized by avoiding the following conditions: (1) Overheating; (2) undue access of air to the oil; (3) conditions likely to give rise to the formation of ozone; (4) contact of the oil with clean surfaces of copper, lead and iron.

365. Specifications. No standard specification for transformer oil is yet available, but a tentative specification has been issued by the War Department, Quartermaster General, Director of Purchase and Storage, Regular Supplies Division, Raw Materials and Paints Branch. Also see manufacturers specifications

GASES

366. The insulating properties of gases depend upon, and vary with, the pressure and the temperature, and are affected also by the humidity. The only gaseous dielectric in extensive use is atmospheric air, whose properties have been the subject of extended research.

367. Air. The dielectric properties of air, and particularly its disruptive strength, have been the subject of more investigation than any other dielectric in use. Extended investigations and researches have been made by Ryan, Mershon, Fisher, Peek, Whitehead, Faccioli, Harding, Bennett, Fortescue and Farnsworth, whose results have been published during the past 15 years in the *Trans.* A. I. E. E., and by Russell (see *Jour.* I. E. E.).

Air in the free state has electrical conductivity. The results obtained (see Whitehead, *Proc.* A. I. E. E., May, 1915, p. 846) indicate that in the open the current passing between two parallel plates 10 cm. apart and each 100 cm. square, assuming perfect insulation, would be of the order of magnitude 3×10^{-16} amp. This is the maximum current which may be obtained and does not increase with increase of voltage; it diminishes greatly if the air is confined in a closed vessel. The conductivity may be greatly increased by exposing the air to Röntgen rays, ultra-violet light, etc., but the magnitude of current still remains very small.

The dielectric constant of air is usually taken as unity, and air is almost universally the medium of reference in all measurements of this constant.

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The disruptive strength of air in a uniform, electrostatic field, under mo favorable conditions, at ordinary temperature and pressure, is of the order 38 kv. per cm. or 97 volts per mil (maximum instead of r.m.s. value); Whit head found a value of 32 kv. (max.) and Peek found a value of 30 kv. (max. Under unfavorable conditions, the strength is below 30 kv. max (21 kv r.m.s.), as shown by investigations of corona on cylindrical wires (see Sec. 11 The disruptive strength is directly proportional to the air density, over a co siderable range. If the air density at 76 cm. barometer and 25 deg. cent. taken as unity, the relative density at any other pressure and temperature

$$\delta = \frac{3.925}{273 + t} \qquad (20$$

where b is the barometer in cm. and t is the temperature in deg. cent. Appa ently the degree of humidity has very often little, if any, effect on the di ruptive strength.

Advantage is taken of the low disruptive strength of air at low pressure (small fraction of one atmosphere) in so-called vacuum-type lightning arre tors, recently developed for low-voltage, low-power circuits, such as tel phone, telegraph and signal lines.

Sparking distances in air, using needle gaps and sphere gaps, are given i the A. I. E. E. Standardization Rules, Sec. 24, Par. 274 to 276.

368. Relative disruptive strengths of hydrogen, oxygen, carbon dioxide and nitrogen

(Wolf)

Pressure in atmospheres	Relative strength (air = 1)				
	Hydrogen	Oxygen	Air	Carbon dioxide	Nitrogen
1	0.87	0.95	1.00	1.20	1.16
2	0.76	0.93	1.00	1.10	1.15
3	0.72	0.92	1.10	1.05	1.15
4	0.69	0.92	1.00	1.03	1.14
5	0.68	0.90	1.00	1.02	1.14

THERMAL CONDUCTIVITIES

369. Thermal conductivities of various insulating materials

(Langmuir, I., *Trans.* A. I. E. E., 1913, Vol. XXXII, p. 303)

Material	Watt-cm. per deg. cent.	Material	Watt-cm. per deg. cent.
Air at 20 deg. cent.	0.000249	Mica, pure	0.0036
Air at 100 deg. cent.	0.000300	Mica paper	0.0016
Asbestos paper	0.0025	Micanite (19 per cent shellac)	0.0010
Bakelite and linen tape	0.0027	Micanite (11 per cent. shellac)	0.0012
Cambric, varnished	0.0025	Paper	0.0013
Cloth, varnished (empire)	0.0025	Paraffin	0.0026
Cotton batting, loose	0.00046	Paraffin oil	0.0014
Cotton batting, tightly packed	0.00030	Petroleum, 23 deg. cent.	0.0016
Cotton tape, varnished	0.0027	Pine, soft white ($\perp$ to grain)	0.0016
Ebonite	0.0018	Porcelain	0.010
Eider down, very loose	0.00045	Pressphan (untreated)	0.0017
Eider down, tightly packed	0.00025	Quartz glass	0.015
Eider down, very tightly packed	0.00019	Rope paper, untreated	0.0012
Fuller board, varnished	0.0014	Rope paper and oil	0.0014
Glass	0.011	Rope paper, treated with varnish	0.0017
Glycerine, 25 deg. cent.	0.0024	Rubber, para	0.0016
Gutta percha	0.0020	Rubber tape	0.0043
Linen tape, varnished and baked	0.0015	Shellac	0.0025
Marble	0.030		

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THERMAL CONDUCTIVITIES.—*Continued*

Material	Watt-cm. per deg. cent.	Material	Watt-cm. per deg. cent.
Slate	0.020	Woolen (pure) wadding, slightly packed	0.00036
Water, 25 deg. cent	0.0057	Woolen (pure) wadding, tightly packed	0.00023
Woolen (pure) wadding, loose	0.00049		

1 watt = 0.2389 g-cal. per sec. 1 g-cal. = 4.186 watt-sec.
1 watt = 0.0009468 B.t.u. per sec. 1 B.t.u. = 251.8 g-cal.
1 g-cal. = 0.003971 B.t.u. 1 B.t.u. = 1,054 watt-sec.

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STRUCTURAL MATERIALS

CAST IRON

371. Cast iron derives its characteristic qualities from the impurities present. These impurities are the same as those in steel, except for graphite, which is one form of carbon. The carbon is always present in two forms: (1) combined carbon, in the form of cementite; (2) uncombined carbon, or graphite. The total carbon seldom exceeds. 4.5 per cent. or falls below 3.25 per cent. The larger the proportion of carbon in the combined state, the harder and more brittle will be the metal. Cast iron is not ductile, in either hot or cold state.

Silicon is a desirable impurity, because it tends to precipitate carbon in the graphitic form; about 3 per cent. of silicon gives the best results. Sulphur has the opposite effect of silicon, and is undesirable. Managnese increases the total carbon and also the proportion of combined carbon, but tends to neutralize the similar effect of sulphur. Phosphorus, if present in sufficient proportions to be chemically active, tends to hold the carbon in combined form, and also tends to weaken the metal.

372. White cast iron. If slowly cooled, white cast iron will contain combined carbon in the form of cementite, which imparts the qualities of hardness and brittleneeas to the metal. Where the carbon is from 3 to 4 per cent., cementite will form from 45 to 50 per cent. of the material. Unless the cooling is slow some of the carbon will be in the austenitic form. White cast iron has few uses, except as a hard coating or skin for gray iron castings.

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373. Gray cast iron usually contains 2 per cent. or more of graphit and less than 1.5 per cent. of combined carbon. The graphite is mechanicall intermingled throughout the body of the metal; although the percentag by weight may be no more than 4 per cent., the percentage by volume ma be as much as 14 per cent. The smaller the proportion of combined carbo the larger will be the proportion of graphite and the softer and more worl able the metal; at the same time this produces a metal of minimum strengt because of its porosity. The interstices are filled with graphite, which act in a degree as a lubricant in machining operations.

Chilled castings are made by pouring cast iron into a metallic mol which cools it rapidly near the surfaces of the casting, thus forming a ski of harder material than the body of the metal. The rapid cooling decreases the proportion of graphite and increases the combined carbon, resulting i the formation of white cast iron.

374. Density of cast iron. Stoughton gives the following densities pure iron, 7.86; white cast iron, 7.60; mottled cast iron, 7.35; light gray cas iron, 7.20; dark gray cast iron, 6.80.

375. Strength of cast iron. (Stoughton)

	Composition				Tensile strength (lb. per sq. in.)
	Silicon (per cent.)	Sulphur (per cent.) (max.)	Phosphorus (per cent.) (max.)	Manganese (per cent.)	
Soft	2.2 to 2.8	0.085	0.70	0.3 to 0.7	28,000
Medium	1.4 to 2.0	0.085	0.70	0.3 to 0.7	30,000
Hard	1.2 to 1.9	0.085	0.7 to 0.4	0.60	25,000

The total range of tensile strength, taking into account all grades of cas iron, is from about 15,000 to 40,000 lb. per sq. in. The compressive strengt is from about 60,000 to 150,000 lb. per sq. in. Young's modulus als varies considerably, an average value being about 15×10^6 lb. per sq. in Also see "Reports of Tests of Metals" (Watertown Arsenal), Gov. Printin Office, Wash. D. C.; annually.

376. Thermal properties. The average specific heat from 20 to 100 deg cent. is 0.119; thermal conductivity, 0.40 watt-cm. per deg. cent.; coefficien of linear expansion, 0.0000106 per deg. cent., at 40 deg. cent.

377. Malleable cast iron. Iron castings in which the majority of th carbon content is in combined form are annealed at 625 to 875 deg. cent. fo about 60 hr. The combined carbon is thereby reduced to graphite, whic occurs in finely powdered form; in the skin of the metal the carbon is elim nated entirely, leaving countless minute cavities. When the castings are made very thin and annealed for a longer period, the carbon can be re moved entirely. If the castings are annealed in lime or fireclay, the carbo is not removed, but deposited as temper carbon. The physical properties lie in the range between gray cast iron and steel castings. The tensil strength ranges between 40,000 and 60,000 lb. per sq. in., with an elongatio of 2 to 6 per cent. and a reduction of area of 2 to 8 per cent.

WROUGHT IRON

378. Pure iron, according to Stoughton, has a tensile strength of abou 45,000 lb. per sq. in. and a compressive strength of about 80,000 lb. pe sq. in. The specific gravity is 7.86.

379. Ingot iron, as it recently has become known in this country, commercially pure iron manufactured by the basic open-hearth proces and it is claimed that the iron content ranges from 99.8 to 99.9 per cen The tensile strength of rolled material is from 42,000 to 44,000 lb. per sq. in elastic limit, 25,000 lb. per sq. in.; elongation, 25 per cent. in 8 in.

380. Thermal properties. The mean specific heat from 0 to 18 de cent. is 0.0986; 15 to 100 deg., 0.115. Thermal conductivity, at 0 deg. cent 0.167 to 0.207 g-cal. (cm-cube) per deg. cent. per sec.; at 18 deg. cent

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0.67 watt-cm. per deg. cent., for pure iron. Coefficient of linear expansion, 0.0000114 per deg. cent., between −18 and 100 deg. cent.

381. Electrolytic iron melted in vacuo, forged into half-inch rods and annealed at 900 deg. cent., has the following average tensile properties.

	Tensile strength (lb. per sq. in.)	Yield point (lb. per sq. in.)	Elongation (per cent.)	Reduction of area (per cent.)
As forged	54,800	48,400	33.3	83.0
Annealed at 900 deg. cent. and cooled in 12 hr.	38,100	18,000	51.8	87.4

The average carbon content of this iron was 0.0125 per cent. See Bulletin No. 72, Eng. Exp. Sta., Univ. of Ill., 1914.

382. Tensile properties of wrought iron. The following properties were taken from Campbell's "Manufacture and Properties of Iron and Steel," 4th edition, p. 91. Also see Holley, "The Strength of Wrought Iron as Affected by its Composition and its Reduction in Rolling," *Trans.* A. I. M. E., Vol. VI, p. 101.

	Minimum	Maximum
Carbon, per cent	0.015	0.512
Phosphorus, per cent	0.065	0.317
Silicon, per cent	0.028	0.321
Manganese, per cent	trace	0.097
Slag, per cent	0.192	2.262
Ultimate strength, lb. per sq. in.	47,478	69,779
Elongation in 8 in., per cent	6.5	32.7
Reduction of area, per cent	7.7	59.8

The general influence of reduction in rolling is to increase the tensile strength and the elastic limit, and diminish the elongation and the reduction of area.

STEEL

383. Carbon steel. Increasing the carbon content of steel increases its strength, hardness, brittleness, and susceptibility to cracking under sudden cooling or heating; it also diminishes the elongation and reduction of area at fracture. In acid steel, according to Campbell, each 0.01 per cent. of carbon increases the strength by 1,000 lb. per sq. in., when the carbon is determined by combustion; or 1,140 lb. per sq. in. when the carbon is determined by color. In basic steel each 0.01 per cent. of carbon increases the strength by 770 lb. per sq. in., when the carbon is determined by combustion, or 820 lb. when determined by color.

Phosphorus increases the tensile strength 1,000 lb. per sq. in. for each 0.01 per cent., but tends to make the metal "cold short" or brittle. **Sulphur** does not alter the tensile strength appreciably, but tends to make the metal "hot short." **Manganese** increases the tensile strength from 80 to 400 lb. per sq. in. for each 0.01 per cent., depending upon the carbon present, and whether the steel is acid or basic; it also increases the ductility when hot. **Silicon** in small quantities has little effect. **Copper** has also little effect on the cold properties as far as known. **Nickel** gives a metal with a high elastic limit and great toughness under shock. **Aluminum** in small quantities is added to molten steel to absorb oxygen and improve the ductility; when present in the finished metal it increases the strength and impairs the ductility.

The thermal conductivity of steel containing 1 per cent. of carbon, at 18 deg. cent., is 0.45 watt-cm. per deg. cent. The coefficient of linear expansion ranges between 0.0000104 and 0.0000132 per deg. cent.

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384. Effect of hot working. The effect of hot-rolling or hammering carbon steel is in general to increase the tensile strength and the elastic limit, and to diminish the elongation and the reduction of area at fracture.

385. Annealing carbon-steel tends to remove the strains created by cold rolling and distortion. In general the effects of annealing are: reduction of tensile strength, elastic limit, and elastic ratio; increase in elongation and reduction of area at fracture. In short, the process of annealing tends to restore the original properties, and to refine the grain or structure.

386. Heat treatment. The finer the grain or structure of steel, in general, the better will be the physical properties. When steel is heated to rolling or forging temperature, the crystalline structure is coarsened, but hot working tends to improve the structure. The best results are obtained by reheating the finished steel to a temperature of about 800 to 900 deg. cent. and allowing it to cool slowly (annealing); the best temperature in any instance depends upon the constituents of the steel. The proper heat treatment of steel is virtually an art in itself. See Howe, H. M., "The Metallography of Steel and Cast Iron," published by McGraw-Hill Book Co., 1916.

387. Hardening and tempering. When high-carbon steel is heated to a medium red and quenched in water or oil it acquires the maximum hardness, becomes brittle, and loses its ductility. The increase in tensile strength due to hardening will vary from about 10 per cent. in steel containing 0.10 carbon to 40 per cent. in steel containing 0.75 carbon. Fully hardened steel is usually too brittle for practical use, and requires softening by drawing the temper; this is accomplished by slowly reheating the steel until its color changes from white to the proper shade, ranging anywhere from straw (high temper) to purple (low temper). See A. S. T. M. specifications.

388. Chrome steel contains usually from 1 to 2 per cent. of chromium and 0.80 to 2 per cent. of carbon. It is characterized by great hardness and high elastic ratio. See "Magnet Steel," Sec. 4. Also see A. S. T. M. specifications.

389. Manganese steel. Hadfield* found that the addition of from 2.5 to 6 per cent. of manganese to steel made the product very brittle, but after the proportion exceeded 7 per cent. there was a return of strength and at 14 to 15 per cent. of manganese a very strong hard alloy was obtained; above 20 per cent. a rapid decrease occurs in strength and toughness. In its most serviceable form, manganese steel contains about 13 to 14 per cent. of manganese, and is practically non-magnetic; on account of its extreme hardness, it is almost impossible to work it with machine tools and it must be cast in the approximate form in which it is to be used. Heating to 1,800 deg. to 2,000 deg. cent. and quenching in cold water, or "water toughening," increases the hardness and resistance to fracture; this is true of both cast and forged material. An alloy of 87 per cent. iron, 12 per cent. manganese and 1 per cent. carbon has a magnetic permeability between 1.3 and 1.5.† The hardness is due partly to the hardness of manganese, and also in large degree to the fact that the steel is in the austenitic condition, which renders it non-magnetic. On account of its hardness it must be cast in the desired form, since it cannot be machined and can be forged only with difficulty.

390. Nickel steel ordinarily contains 1.5 to 4.5 per cent. of nickel and 0.20 to 0.50 per cent. of carbon. About 3.5 per cent. of nickel added to carbon-steel will increase the elastic limit nearly 50 per cent. and reduce the ductility about 15 or 20 per cent. The tensile strength is increased also, but not in as large proportion as the elastic limit. The notable increase in elastic limit and elastic ratio is accompanied by an increased resistance to fatigue under repeated stress. In low-carbon steels, the addition of each 1 per cent. of nickel, up to 5 per cent., increases the elastic limit 5,000 lb. per sq. in. and the tensile strength 4,000 lb. per sq. in.; these effects increase with higher percentages of carbon. The resistance to compression is also greater. The value of Young's modulus is the same as for carbon-steel. Nickel steel has a higher resistance to wear or abrasion than carbon-steel, and greater resistance to corrosion. Special alloys very high in nickel are known as Invar and Platinite; **Invar** contains 36 per cent. of nickel and its coefficient of expansion

* Hadfield, R. A. *Trans.* Amer. Inst. of Mining Eng., 1893, Vol. XXIII p. 148; *Jour.* Iron and Steel Inst., 1888, No. 2, p. 41; *Proc.* Inst. of Civ. Eng. 1887–1888, Vol. XCIII, Part 3, p. 1.
Hall, J. H. "Manganese Steel," *Proc.* Soc. of Chem. Industry, 1914.

† Ewing, J. A. "Magnetic Induction in Iron and Other Metals."

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is practically zero. **Platinite** (42 per cent. Ni) has the same coefficient of expansion as glass. See Colby, A. L. "Nickel Steel," *Proc.* A. S. T. M., Vol. III, 1903.

391. Silicon steel.* The addition of silicon to steel appears to increase the strength about 80 lb. per sq. in. for every 0.01 per cent., up to a content of 4 per cent.; beyond this point it severely impairs the ductility. A steel containing 3.40 silicon, 0.21 carbon and 0.29 manganese had a tensile strength of 106,000 lb. per sq. in.; elastic ratio, 0.74; elongation, 11 per cent.; reduction of area, 14 per cent.; annealed strength, 87,000 lb. per sq. in. The silicon content in structural steels, when used, is ordinarily limited to 0.40 per cent., in order to avoid brittleness. Silicon is used in electrical sheets, because it substantially increases the electrical resistivity and thus reduces the core loss; such sheets are much harder than ordinary dynamo sheets of soft steel; see "Magnetic Materials" in this section. The thermal conductivity of 4 per cent. silicon-steel, between 20 and 250 deg. cent., is 0.32 watt-cm. per deg. cent.

392. Tungsten steel is characterized by great hardness and toughness and its remarkable tempering properties. The tungsten content ranges from 0.5 per cent. in ordinary bar steel to 2 to 5 per cent. in finishing and intermediate steels, 4.5 to 12 per cent. in self-hardening or air-hardening steels, and 14 to 26 per cent. in high-speed steels. See Baskerville, C. "The Chemistry of Tungsten, Etc.," *Trans.* N. Y. Elec. Soc., Oct. 29, 1912; also see "Magnet Steel," Sec. 4.

393. Vanadium steel. The use of vanadium as a constituent in alloy steel produces more remarkable results than any other element except carbon. Oil-tempered vanadium steel containing 0.25 to 0.30 carbon, 0.50 manganese, 1.0 chromium and 0.17 vanadium has been found to have a tensile strength as high as 233,000 lb. per sq. in., elastic ratio 96 per cent., elongation 11 per cent., and contraction of area 39 per cent. The vanadium content is usually less than 0.3 per cent.; its effect in general is to improve the tensile properties, hardness and toughness.

394. Protective coatings for iron and steel consist of the following: (a) pigments of various kinds; (b) galvanizing or zinc coating, applied by hot-dipping, electroplating or dry-heating with zinc dust; (c) coating with aluminum alloy, by dry-heating with the powdered alloy; (d) tinning, by hot-dipping and rolling; (e) terne coating, of lead-tin alloy, applied in the same manner as tinning; (f) nickel-plating, applied electrolytically; (g) coating of black oxide of iron, produced by application of oil to the metal when black hot; (h) enamel coating of glass. For out-door exposures, methods (a) and (b) are the ones chiefly used, but neither is free from faults or objections. For particulars see Wood, M. P. "Rustless Coatings; Corrosion and Electrolysis of Iron and Steel," New York, 1905; "Report of the Committee on Preservative Coatings for Structural Materials," 1903 to 1913, A. S. T. M., Phila., Pa.; Bulletins No. 30, 35 and 239, U. S. Dept. of Agriculture, Wash., D. C. Stoughton, B. "The Metallurgy of Iron and Steel," McGraw-Hill Book Co., Inc., New York, 1911. Cushman and Gardner. "Corrosion and Preservation of Iron and Steel," McGraw-Hill Book Co., Inc., New York, 1910.

STEEL WIRE AND CABLE

395. Table of steel wire

(Roebling)

Number, Roebling gage	Diameter in inches	Area in square inches	Breaking load at rate of 100,000 lb. per sq. in.	Weight in pounds	
				Per 1,000 ft.	Per mile
000000	0.460	0.1662	16,620	558.4	2,948
00000	0.430	0.1452	14,520	487.9	2,576
0000	0.393	0.1213	12,130	407.6	2,152
000	0.362	0.1029	10,290	345.8	1,826
00	0.331	0.08605	8,605	289.1	1,527
0	0.307	0.07402	7,402	248.7	1,313

*Hadfield, R. A. *Jour.* Iron and Steel Inst., 1889; *Jour.* Inst. of Elec. Eng., 1892; Royal Dublin Society, 1900 and 1904; *Trans.* Faraday Society, 1914.

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395. Table of steel wire.—*Continued*

(Roebling)

Number, Roebling gage	Diameter in inches	Area in square inches	Breaking load at rate of 100,000 lb. per sq. in.	Weight in pounds	
				Per 1,000 ft.	Per mile
1	0.283	0.06290	6,290	211.4	1,116
2	0.263	0.05433	5,433	182.5	964
3	0.244	0.04676	4,676	157.1	830
4	0.225	0.03976	3,976	133.6	705
5	0.207	0.03365	3,365	113.1	597
6	0.192	0.02895	2,895	97.3	514
7	0.177	0.02461	2,461	82.7	437
8	0.162	0.02061	2,061	69.3	366
9	0.148	0.01720	1,720	57.8	305
10	0.135	0.01431	1,431	48.1	254
11	0.120	0.01131	1,131	38.0	201
12	0.105	0.008659	866	29.1	154
13	0.092	0.006648	665	22.3	118
14	0.080	0.005027	503	16.9	89.2
15	0.072	0.004071	407	13.7	72.2

This table was calculated on a basis of 483.84 lb. per cu. ft. for stee wire. Iron wire is a trifle lighter. The breaking loads were calculate for 100,000 lb. per sq. in. throughout, simply for convenience, so tha the breaking loads of wires of any strength per sq. in. may be quickl determined by multiplying the values given in the table by the ratio betwee the strength per sq. in. and 100,000. As a matter of fact the strength range from 45,000 lb. for soft annealed to over 400,000 lb. per sq. in. for hard wire

396. Galvanized steel signal wire in sizes of No. 8 and No. 9 B.W.G. i manufactured (Amer. Steel and Wire Co.) with approximate breakin strengths of 2,350 lb. and 1,900 lb., respectively. It is used for operatin semaphore signals from levers in a mechanical interlocking machine (Sec. 16)

397. Table of galvanized steel cable or messenger strand; standard steel, open-hearth steel, crucible steel and plow steel

(American Steel and Wire Co.)

Diam. (in.)	Lb. per 1,000 ft.	Ultimate total strength (lb.)			
		Standard steel strand	Siemens-Martin (open-hearth) strand	High-strength (crucible steel) strand	Extra high-strength (plow steel) strand
1	2,250	.....	51,000	87,400	120,000
$\frac{7}{8}$	1,700	.....	38,000	64,000	90,000
$\frac{3}{4}$	1,250	.....	28,400	47,400	70,000
$\frac{5}{8}$	810	.....	19,000	25,000	42,500
$\frac{9}{16}$	510	8,500	11,000	18,000	27,000
$\frac{1}{2}$	415	6,500	9,000	15,000	22,500
$\frac{7}{16}$	295	5,000	6,800	11,500	17,250
$\frac{3}{8}$	210	3,800	4,860	8,100	12,100
$\frac{5}{16}$	.....	.....	4,380	7,300	10,900
$\frac{1}{4}$	125	2,300	3,060	5,100	7,600
$\frac{7}{32}$	95	1,800	.....	.....	.....
$\frac{3}{16}$	75	1,400	2,000	3,300	4,900

A special $\frac{1}{4}$-in. Siemens-Martin strand is manufactured, having a ultimate strength of 6,000 lb. See Technologic Paper No. 121, Bur. of Stds

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396. Tensile tests of steel spring wire, of best quality tempered music-wire, from about 0.04 to 0.05 in. in diameter, gave from 342,000 to 358,000 lb. per sq. in.; elongation between 1 and 2 per cent.; contraction of area, 38 to 46 per cent. (Report of Tests of Metals, 1904; Watertown Arsenal).

NON-FERROUS METALS AND ALLOYS

399. Properties of miscellaneous non-ferrous metals and alloys

(Compiled from various authorities)

Metal	Density	Strength (1,000 lb. per sq. in.)		Young's modulus (10^6 lb. per sq. in.)	Coefficient of expansion per deg. cent. $\times 10^{-6}$	Thermal conductivity (g-cal. per cm-cube per deg. cent. per sec.)
		Tension	Compression			
Aluminum, cast	2.56	12–15	12	9–11	.....	.....
Aluminum, rolled	2.68	24–40	.....	11	23.1	0.34
Aluminum, wire	2.70	20–40	.....	9–12	23.1	0.34
Aluminum, alloys	2.7–3.1	15–45	16–100	.....	.....	.....
Aluminum, bronze	7.7–8.3	60–90	120	.....	.....	.....
Brass, cast	8.5	18–24	30	9	17–22	0.23
Brass, wire	8.46	40–150	.....	14	.....	0.31
Bronze, bearing	8.5–8.9	25–50	80	.....	17–22	.....
Bronze, gun metal	.....	25–55	.....	10–12	.....	.....
Bronze, manganese	8.4	75–90	125–150	15	.....	.....
Bronze, phosphorus	.....	35–50	.....	14	17	.....
Bronze, phosphorus, hard-drawn.	.....	110–140	.....	.....	17	.....
Bronze, silicon	.....	55–75	.....	.....	.....	.....
Bronze, silicon, hard-drawn.	.....	95–115	.....	.....	.....	.....
Bronze, Tobin	8.40	60–100	180	4.5	.....	.....
Copper, cast	8.5–8.9	22–25	40–60	10–12	.....	.....
Copper, rolled	8.9	29–35	.....	.....	16.7	0.84
Copper, wire	8.89	35–70	.....	12–16	16.7	0.84
Delta metal, cast	.....	45	.....	.....	.....	.....
Delta metal, rolled	.....	70–85	.....	13	.....	.....
Delta metal, wire	.....	100	.....	.....	.....	.....
Duralumin	2.8	50–60	44	10.6	2.26	.....
Gold	19.3	20–30	.....	8	14.4	0.70
Gun metal	.....	22–27	.....	10–11	.....	.....
Lead	11.3	1.6–3.0	.....	.....	28.	0.084
Magnesium	1.74	30	.....	.....	26.	0.37
Monel metal	8.87	70–110	.....	22–23	13.8	.....
Nickel	8.6–8.9	40–85	.....	24–27	12.6	0.14
Palladium	11.4	39	.....	.....	11.	0.17
Platinum	21.4	30–50	.....	.....	8.8	0.17
Silver	10.5	40–45	.....	.....	19.	1.10
Tin	7.30	3.5–5	.....	4	21.	0.15
Zinc, cast	6.87	6–13	18	11–13	26.	.....
Zinc, rolled	7.19	22–28	.....	11–13	26.	0.27

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CONCRETE, BRICK AND STONE

400. The composition of normal Portland cement* has been th subject of a great deal of investigation and it can be said that the quantitie of silica, alumina, oxide of iron, lime, magnesia, and sulphuric anhydride ca vary within fairly wide limits without materially affecting the quality of th material. A normal American Portland cement which meets the standar specifications for soundness, setting time and tensile strength has an approxi mate composition within the following percentage limits:

Silica	19–25	Magnesia	1–4
Alumina	5–9	Sulphur trioxide	1–1.75
Iron oxide	2–4	Loss on ignition	0.5–3.00
Lime	60–64	Insoluble residue	0.1–1.00

It is also true that a number of cements have been made both here an abroad which have passed all standard physical tests in which these limit have been exceeded in one or more particulars, and it is equally true that sound and satisfactory cement does not necessarily result from the abov composition. Defective cement usually results from imperfect manufacture not from faulty composition. Cement made from very finely groun material, thoroughly mixed and properly burned, may be perfectly soun when containing more than the usual quantity of lime, while a cement low i lime may be entirely unsound due to careless manufacture. Also see Sec. 1 Par. **255** *et seq.*

401. Standard methods of testing cement are described in Circula No. 33, Bureau of Standards, pages 9 to 28. Also see circular No. 39, i *re* standard sieves. Also see A. S. T. M. specifications.

402. Neat cement is Portland cement mixed with enough water to wor it, and without the use of any aggregates (sand, gravel or stone). Whe such a mixture is made thin enough to pour, it is termed **grout.** Nea cement is employed in cementing together parts of large porcelain insulators or cementing the insulators to their supporting members.

403. Crushing strength of concrete. (Smithsonian Phys. Table 1910; based on data furnished by the U. S. Geol. Survey.)

Coarse aggregate	Proportions by volume; cement-sand-aggregate	Lb. per sq. in.
Sandstone	1–5–14 to 1–1–5	1,550 to 3,860
Cinders	1–3– 6 to 1–1–3	790 to 2,050
Limestone	1–4– 8 to 1–2–4	1,200 to 2,840
Conglomerate	1–6–12 to 1–2–4	1,080 to 3,830
Trap	1–2– 9 to 1–2–4	820 to 2,960

Test pieces were 12-in. cubes. Also see Bulletins of Eng. Exp. Sta Univ. of Ill.; publications of the Geological Survey; publications of th Bureau of Standards.

404. Weight of concrete. The weight of stone and gravel concrete 1:2:4 mixture, may be taken as 150 lb. per cu. ft.; cinder concrete, 120 lb.

405. Reinforced concrete. See Sec. 23, Par. **12** to **17** and Par. **24**

406. Crushing strength of brick. (Smithsonian Phys. Tables, 1910 based on data furnished by the U. S. Geol. Survey.)

Kind of brick	Lb. per sq. in.	
	Tested flatwise	Tested on edge
Soft burned	1,800 to 4,000	1,600 to 3,000
Medium burned	4,000 to 6,000	3,000 to 4,500
Hard burned	6,000 to 8,500	4,500 to 6,500
Vitrified	8,500 to 25,000	6,500 to 20,000
Sand-lime	1,800 to 4,000	....

* Quotation from Circular No. 33, U. S. Bureau of Standard; pp. 18 and 1

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Brick piers laid up in 1 part Portland cement, and 3 of sand, have from 20 to 40 per cent. of the crushing strength of the brick. Also see "Report of Tests of Metals," Gov. Printing Office, Washington, D. C., 1909.

407. Fire-brick when tested on end, at atmospheric temperature, should exhibit a crushing strength of more than 1,000 lb. per sq. in. More important is the ability to withstand a compression load of 50 lb. per sq. in. at 1,350 deg. cent. without failure; if the specimen shows marked deformation or contracts more than 1 in. in the standard length of 9 in., failure is considered to have taken place. Fire-brick should have average melting points as follows, in deg. cent.: fire clay, 1,650; bauxite, 1,695; silica, 1,700; chromite, 2,050; magnesia, 2,165. Also see "A. S. T. M. Tentative Standards."

408. Clay tile. The strength of drain tile is covered by standard specifications of the A. S. T. M. Also see Bulletins No. 31 and No. 36, Iowa Eng. Exp. Sta., Ames, Ia.

409. Crushing strength of stone. (Smithsonian Phys. Tables, 1910; based on data furnished by U. S. Geol. Survey.)

Material	Size	Lb. per sq. in.
Marble	4-in. cubes	7,600 to 20,300
Brownstone		7,300 to 23,600
Sandstone	4-in. cubes	2,400 to 29,300
Granite	4-in. cubes	9,700 to 34,000
Limestone	4-in. cubes	6,000 to 25,000

TIMBER

410. Wood consists of a skeleton of cellulose permeated by a mixture of other organic substances collectively known as lignum, and particles of mineral matter (or ashes). Wood dried at 300 deg. fahr. is comprised of more than 99 per cent. organic matter, and less than 1 per cent. inorganic or non-combustible matter. In 100 lb. of wood dried at 300 deg. fahr. will be found about 49 lb. of carbon, 6 lb. of hydrogen and 44 lb. of oxygen; the composition is fairly uniform for the different species.

411. Spring wood and summer wood in coniferous trees are distinguished by the different colors in each ring. The inner light-colored portion of a ring is termed the spring wood, and the outer dark-colored portion is the summer wood. In oak and other broad-leaved woods, however, the darker portions are the spring wood and the lighter parts are summer wood.

412. Annual or yearly concentric rings which appear at the cross-section of a log are so many thin layers of wood, forming a consecutive series of enveloping cones, each ring or cone representing one year's growth. As a rule the rings are widest near the pith or centre of the tree.

413. Sapwood and heartwood. A zone of wood next to the bark, 1 in. to 3 in. or more wide, of light color and containing 30 to 50 or more annual rings, is the sapwood; the darker central portion is the heartwood. Only the outer portions of the sapwood assist in the growing processes and ultimately the sapwood changes to heartwood. The cells of the latter are lifeless and serve merely a structural function. The proportion of sapwood in coniferous trees constitutes 40 per cent. or more of the bulk, and a much larger proportion in young trees.

414. Moisture in wood. Water occurs in wood in three forms: (1) it forms the greater part (over 90 per cent.) of the protoplasmic contents of the living cells; (2) it saturates the walls of all cells; (3) it wholly or partly fills the cavities of the lifeless cells. In drying green wood in a kiln, from 40 to 65 per cent. of the weight of the sapwood and 16 to 40 per cent. of the weight of the heartwood are lost as excluded moisture. The weight is obviously dependent in large degree on the extent of seasoning or drying.

415. Shrinkage takes place as green wood is dried, but does not commence until the fibre saturation point is reached; then it commences to shrink both laterally and longitudinally, but the latter in most species is negligible. The shrinkage of transverse area in drying from green to oven-dry condition (3.5 per cent. of moisture) varies with different species from as much as 20 per cent. with hickory to as low as 7 per cent. with red cedar. The radial

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shrinkage in poles is usually small; the circumferential shrinkage in chestnut poles 1 year after cutting has been found not to exceed 1 per cent.

416. Specific gravity and fibre saturation point. The following table was abstracted from Circular No. 108, "The Strength of Wood as Influenced by Moisture," by H. D. Tiemann, U. S. Forest Service, p. 11.

Species (small test specimens)	Average density (kiln-dry)	Per cent. moisture at fibre saturation
Long-leaf pine	0.62	25
Red spruce	0.38	31
Chestnut	0.48	25
Loblolly pine, green heartwood	0.59	23
Loblolly pine, air-dry heartwood	0.67	24
Loblolly pine, green sapwood	0.47	24
Loblolly pine, air-dry sapwood	0.55	26
White ash	0.79	20
Red gum, air-dry	0.52	25
Douglas fir	0.58	23
Norway pine, heartwood	0.42	30
Norway pine, sapwood	0.44	28
Tamarack	0.54	30

417. Specific heat of oven-dry wood, based on 100 determinations with 20 different species, was found to be represented by the formula

$$\text{Sp. heat} = 0.266 + 0.00116t \qquad (21)$$

for a range from 0 deg. to 106 deg. cent. The average was 0.327, with a maximum of 0.337 (for longleaf pine) and a minimum of 0.317 (for chestnut). The material tested showed a variation of from 3 to 20 rings per cm. and a range of 0.40 to 0.59 in density. See Bulletin No. 110, U. S. Forest Service; 1912.

418. Standard names and standard defects of structural timber were defined and adopted by the Amer. Soc. for Testing Materials, on Sept. 1, 1907; see "A. S. T. M. Standards."

419. Effect of moisture on strength. Moisture is found in green wood in two states—that which is in the walls of the cells and that which fills the pores. The latter has no influence on the strength. The point at which the cell walls become saturated with water, although the pores may continue to absorb it, is termed the **fibre saturation point.** When the absorption of moisture continues past the fibre saturation point, there is no further swelling of the wood and no further effect upon the strength.

Green timber is in general weaker than seasoned or dry timber, except as to shearing resistance parallel to the grain. While reduction of the moisture content tends of itself to increase the strength, the seasoning process also has a counter-tendency or weakening effect which results from the formation of checks. The increase in strength due to drying is especially marked in small pieces free from defects, but large timbers almost invariably form checks during seasoning and it is not in general safe to count upon any increase in strength. In the case of structural timbers it is safest always to determine the strength from tests on pieces of the size and in the condition in which they will be used. For further particulars see Bulletin No. 70, Bulletin No. 108 and Circular No. 108, U. S. Forest Service, Wash., D. C.

420. Working unit stresses for structural timber, as adopted by the American Railway Engineering Association, are given in the table below. The working unit stresses given in the table are intended for railroad bridges and trestles. For highway bridges and trestles, the unit stresses may be increased 25 per cent. For buildings and similar structures, in which the timber is protected from the weather and practically free from impact, the unit stresses may be increased 50 per cent. To compute the deflection of a beam under long continued loading instead of that when the load is first applied, only 50 per cent. of the corresponding modulus of elasticity given in the table is to be employed.

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Working unit stresses for structural timber (Par. 420)
(Unit stresses in pounds per square inch)

Kind of timber	Bending			Shearing				Compression					
	Extreme fiber stress		Modulus of elasticity	Parallel to the grain		Longitudinal shear in beams		Perpendicular to the grain		Parallel to the grain		Working stresses for columns	
	Average ultimate	Working stress	Average	Average ultimate	Working stress	Average ultimate	Working stress	Elastic limit	Working stress	Average ultimate	Working stress	Length under 15×d	Length over 15×d
Douglas Fir	6100	1200	1510000	690	170	270	110	630	310	3600	1200	900	1200 (1—L/60D)
Long-leaf Pine	6500	1300	1610000	720	180	300	120	520	260	3800	1300	975	1300 (1—L/60D)
Short-leaf Pine	5600	1100	1480000	710	170	330	130	340	170	3400	1100	825	1100 (1—L/60D)
White Pine	4400	900	1130000	400	100	180	70	290	150	3000	1000	750	1000 (1—L/60D)
Spruce	4800	1000	1310000	600	150	170	70	370	180	3200	1100	825	1100 (1—L/60D)
Norway Pine	4200	800	1190000	590*	130	250	100	.....	150	2600*	800	600	800 (1—L/60D)
Tamarack	4600	900	1220000	670	170	260	100	.....	220	3200*	1000	750	1000 (1—L/60D)
Western Hemlock	5800	1100	1480000	630	160	270*	100	440	220	3500	1200	900	1200 (1—L/60D)
Redwood	5000	900	800000	300	80	.....	.....	400	150	3300	900	675	900 (1—L/60D)
Bald Cypress	4800	900	1150000	500	120	.....	.....	340	170	3900	1100	825	1100 (1—L/60D)
Red Cedar	4200	800	800000	.....	.....	.....	.....	470	230	2800	900	675	900 (1—L/60D)
White Oak	5700	1100	1150000	840	210	270	110	920	450	3500	1300	975	1300 (1—L/60D)

Unit stresses are for green timber and are to be used without increasing the live load stresses for impact. Value noted * are for partially air-dry timber. In the formulas given for columns, L = length of column, in inches, and D = least side or diameter, in inches.

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421. Tests of maple and hickory
(Lb. per sq. in.)

	Elastic limit			Maximum load		
	Aver.	Max.	Min.	Aver.	Max.	Min.
Maple	8895	9950	7370	14,130	17,600	9,800
Hickory	8063	9150	7440	16,000	17,100	13,900

See Circular No. 42 and Bulletin No. 80, U. S. Forest Service, Wash., D. C.

422. Standard specifications for yellow-pine bridge and trestle timbers were adopted in 1910 by the Amer. Soc. for Testing Materials; see "A. S. T. M. Standards."

423. Weight and seasoning of poles. The dry weight of cedar is 20.7 lb. per cu. ft. Green cedar poles weigh approximately 35 to 40 lb. per cu. ft. when cut, and fall to about 25 lb. per cu. ft. in 10 to 18 months of seasoning. Air-dry cedar contains about 20 per cent. of moisture and weighs from 65 to 70 per cent. of the green weight. The dry weight of chestnut is 28.1 lb. per cu. ft. Green chestnut poles weigh approximately 52 to 56 lb. per cu. ft. when cut, and fall to 40 to 45 lb. per cu. ft. in 8 to 24 months of seasoning. The specific gravity of green chestnut is 0.85 to 0.86. All things considered, winter-cut poles are the most desirable. They season more regularly and are more immune to decay than those cut in other seasons.

424. Working unit stresses for wood poles, adopted by the N. E. L. A.* and the A. E. R. E. A.,† are as follows, in lb. per sq. in.

Eastern white cedar	600	Douglas fir	900
Chestnut	850	White oak	950
Washington cedar	850	Redcedar	700
Idaho cedar	850	Bald cypress (heartwood)	800
Port Orford cedar	1150	Redwood	650
Long-leaf yellow pine	1000	Catalpa	500
Short-leaf yellow pine	800	Juniper	550

The above values apply to bending; in compression the above values should be multiplied by the factor $(1-L/60D)$, where L is the length in inches and D is the least side or diameter in inches. The maximum allowable fiber stress permitted under the National Electrical Safety Code is 2,500 lb. per sq. in. for chestnut, western red cedar and cypress and 1,800 lb. per sq. in. for northern white cedar and redwood; both figures are one-half of the assumed ultimate strength.

425. Decay and its prevention. At ordinary temperatures wood is a very stable compound and unless attacked by living organisms it remains the same for centuries, either in air or under water. Bacteria and fungi are the chief enemies of wood, and they thrive best with warmth and abundance of moisture and air. Contact with the ground results in the most favorable condition for fungus growth; the higher temperatures near the surface of the ground, together with the prevalence of spores, cause decay to start sooner at the surface than 2 or 3 ft. below the surface. Perfect seasoning, together with the use of means of protection against the entrance of moisture, and impregnating compounds (creosote or bichloride of zinc) which prevent fungi from feeding on the wood, are the best means of preservation. The sapwood is more vulnerable than heartwood, but wood cut in the late fall or winter is more durable than that cut in the late spring or summer. The different species, however, differ materially in their resistance to decay. See "Wood Preservation in the U. S.," by W. F. Sherfesee; U. S. Forest Service, Bulletin No. 78; 1909.

426. Methods of applying preservatives. The closed-tank method is employed where it is desirable to treat each entire stick or member, such as cross-ties and cross-arms. In the pressure process live steam is first admitted for a time; next this is withdrawn and a vacuum established;

* Report of the Joint Committee on Overhead Line Construction; 1913.
† Report of the Committee on Power Distribution; 1913.

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finally the preservative is introduced under pressure. This method secures the maximum penetration and absorption.

The open-tank treatment, hot process at atmospheric pressure, is used extensively for treating the butts of poles. The penetration in open-grained porous wood is from 0.75 to 1.00 in., and in dense wood from 0.25 to 0.50 in. The brush treatment secures a penetration ranging from 0.06 to 0.25 in., or from two to three annual rings. The absorption in all cases is increased by seasoning. Also see Bulletin No. 78, U. S. Forest Service, 1909.

427. Strength of treated timber. Talbot concluded from his tests of timber (Bulletin No. 41, Eng. Exp. Sta., Univ. of Ill., 1909; also see Forest Service Circular No. 39) that creosoting, under ordinary practice, decreases the strength and the stiffness. Also see Forest Service Bulletin No. 556, issued by the Dept. of Agriculture.

ROPE AND BELTING

428. Manila rope. The weight of Manila rope, based on the tests of the C. W. Hunt Co., is expressed by the formula

$$\text{Wt. per ft.} = 0.34d^2 \qquad \text{(lb.)} \qquad (22)$$

where d is the diameter in inches. The tensile strength is given by the formula

$$T = 7{,}160d^2 \qquad \text{(lb.)} \qquad (23)$$

where T is the total strength of the rope and d is the diameter in inches. Kirsch concluded from his tests that a rope having a diameter of 1 in. would have an average breaking strength as follows: **Italian hemp,** 9,910 lb.; Hungarian hemp, 9,293 lb.; Manila rope, 7,100 lb.

The Plymouth Cordage Co. gives the following rules for Manila rope: the weight per ft. is equal to the square of the diameter in inches, multiplied by 0.34; the breaking strength is equal to the square of the diameter, multiplied by 7,500; the maximum permissible tension (rope drives) is equal to the square of the diameter, multiplied by 200.

The C. W. Hunt Co. gives factors of safety, for computing the allowable working loads, approximately as follows: tackle, 7; hoisting, 18; transmission, 35. The efficiency of knots in rope ranges from 50 to 90 per cent.

For further data on tests of rope, see "Tests of Metals," reporting Watertown Arsenal tests, Gov. Printing Office, Wash., D. C. Also see U. S. Government Specifications.

429. Danger of metal filaments or strands in rope. Metal filaments are sometimes introduced in ropes to give added strength; when such ropes are used by linemen they become exceedingly dangerous, owing to the probability of communicating electrical shock. Similar danger exists from tape lines made of a fabric base and containing metal threads.

430. Leather belting weighs about 60 lb. per cu. ft. and has a tensile strength of from 2,000 to 5,000 lb. per sq. in., or an average of about 650 lb. per in. of width of single belt. See tests of leather belting in Watertown Arsenal Reports ("Tests of Metals") for 1893, Gov. Printing Office, Wash., D. C.

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PROPERTIES OF THE ELEMENTS

432. Atomic weights, densities, specific heats and melting points of the elements in solid or fluid state. Compiled from International atomic weights (1917), "Smithsonian Phys. Tables" (1920) and Circular No. 35 of the Bureau of Standards (1912).

Element	Symbol	Atomic weight	Density	Specific heat	Melting point (deg. cent.)
Aluminum	Al	27.1	2.70	0.212	658.7
Antimony	Sb	120.2	6.69	0.049	630
Argon	A	39.88	1.40	.....	−188
Arsenic	As	74.96	5.73	0.084	850
Barium	Ba	137.37	3.75	0.068	850
Bismuth	Bi	208.0	9.78	0.030	271
Boron	B	11.0	2.53	0.307	2350
Bromine	Br	79.92	3.12	0.107	−7.3
Cadmium	Cd	112.40	8.67	0.055	320.9
Caesium	Cs	132.81	1.87	0.048	26
Calcium	Ca	40.07	1.54	0.170	810
Carbon	C	12.005	3.51	0.113	>3600
Cerium	Ce	140.25	7.02	0.045	640
Chlorine	Cl	35.46	1.507	0.226	−101.5
Chromium	Cr	52.0	6.92	0.104	1615
Cobalt	Co	58.97	8.71	0.103	1478
Columbium	Cb	93.1	8.4	.....	2200
Copper	Cu	63.57	8.89	0.092	1083.0
Dysprosium	Dy	162.5	.....	.....	.....
Erbium	Er	167.7	4.77	.....	.....
Europium	Eu	152.0	.....	.....	.....
Fluorine	F	19.0	1.14	.....	−223
Gadolinium	Gd	157.3	.....	.....	.....
Gallium	Ga	69.9	5.93	0.080	30
Germanium	Ge	72.5	5.46	0.074	958
Glucinum	Gl	9.1	1.85	.....	.....
Gold	Au	197.2	19.33	0.032	1063.0
Helium	He	4.00	0.15	.....	< −271
Holmium	Ho	163.5	.....	.....	.....
Hydrogen	H	1.008	0.070	.....	−259
Indium	In	114.8	7.27	0.057	155
Iodine	I	126.92	4.94	0.054	113.5
Iridium	Ir	193.1	22.42	0.032	2300
Iron	Fe	55.84	7.865	0.115	1530
Krypton	Kr	82.92	2.16	.....	−169

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Table 432.—*Continued*

Element	Symbol	Atomic weight	Density	Specific heat	Melting point (deg. cent.)
Lanthanum	La	139.0	6.15	0.045	810
Lead	Pb	207.20	11.34	0.030	327.4
Lithium	Li	6.94	0.534	0.85	186
Lutecium	Lu	175.0	.....	.....	.....
Magnesium	Mg	24.32	1.741	0.249	651
Manganese	Mn	54.93	7.42	0.111	1230
Mercury	Hg	200.6	13.55	0.033	−38.9
Molybdenum	Mo	96.0	9.01	0.064	2535
Neodymium	Nd	144.3	6.96	.....	840
Neon	Ne	20.2	.....	.....	−253
Nickel	Ni	58.68	8.80	0.109	1452
Niton	Nt	222.4	.....	.....	.....
Nitrogen	N	14.01	0.83	.....	−211
Osmium	Os	190.9	22.5	0.031	2700
Oxygen	O	16.00	1.14	.....	−218
Palladium	Pd	106.7	12.16	0.059	1549
Phosphorus	P	31.04	2.34	0.19	44
Platinum	Pt	195.2	21.37	0.032	1755
Potassium	K	39.10	0.87	0.170	62.3
Praseodymium	Pr	140.9	6.475	.....	940
Radium	Ra	226.0	.....	.....	700
Rhodium	Rh	102.9	12.44	0.058	1950
Rubidium	Rb	85.45	1.532	0.080	38
Ruthenium	Ru	101.7	12.06	0.061	>1950
Samarium	Sa	150.4	7.75	.....	1350
Scandium	Sc	44.1	.....	.....	.....
Selenium	Se	79.2	4.55	0.068	218.5
Silicon	Si	28.3	2.42	0.175	1420
Silver	Ag	107.88	10.6	0.055	960.5
Sodium	Na	23.0	0.971	0.253	97.5
Strontium	Sr	87.63	2.54	.....	.....
Sulphur (S_8)	S	32.06	2.05	0.173	112.8
Tantalum	Ta	181.5	16.6	0.033	2900
Tellurium	Te	127.5	6.25	0.048	452
Terbium	Tb	159.2	.....	.....	.....
Thallium	Tl	204.0	11.85	0.033	302
Thorium	Th	232.4	12.16	0.027	>1700
Thulium	Tm	168.5	.....	.....	.....
Tin	Sn	118.7	7.30	0.054	231.9
Titanium	Ti	48.1	4.5	0.110	1795
Tungsten	W	184.0	18.85	0.034	3400
Uranium	U	238.2	18.7	0.028	<1850
Vanadium	V	51.0	5.69	0.115	1720
Xenon	Xe	130.2	3.52	.....	−140
Ytterbium	Yb	173.5	.....	.....	.....
Yttrium	Y	88.7	3.8	.....	1490
Zinc	Zn	65.37	7.19	0.093	419.4
Zirconium	Zr	90.6	6.44	0.066	1700

433. Density of water, from 0 to 100 deg. cent. (Circular No. 19, Bureau of Standards).

Temp.	Density	Temp.	Density	Temp.	Density	Temp.	Density
0	0.99987	25	0.99707	50	0.98807	75	0.97489
4	1.00000	30	0.99567	55	0.98573	80	0.97183
10	0.99973	35	0.99406	60	0.98324	85	0.96865
15	0.99913	40	0.99224	65	0.98059	90	0.96534
20	0.99823	45	0.99024	70	0.97781	100	0.95838

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434. Specific heat of water, from 0 to 100 deg. cent. (Smithsonian Phys. Tables, 1920).

Temp.	Sp. ht.	Temp.	Sp. ht.	Temp.	Sp. ht.	Temp.	Sp. ht.
0	1.0094	20	0.9990	50	0.9980	80	1.0042
10	1.0023	30	0.9976	60	0.9994	90	1.0070
15	1.0003	40	0.9974	70	1.0015	100	1.0101

435. Atmospheric air* contains oxygen, nitrogen, carbon dioxide, water vapor and argon. The constituents of pure dry air are as follows:

	By weight, per cent.	By volume, per cent.
Nitrogen	75.50	78.06
Oxygen	23.20	21.00
Argon	1.3	0.94
	100.00	100.00

Free air contains from 3 to 4 parts of CO_2 in 10,000 parts by volume. The standard atmospheric pressure is 29.92 in. (760 mm.) of mercury. The amount of water vapor contained in air depends upon the temperature and the degree of saturation; the ratio of the amount of vapor actually present to that amount required to saturate the air is termed the relative humidity. See "Smithsonian Physical Tables," 7th rev. ed., 1920.

436. Weight of dry air. Computed from the formula $w=[1.293052/-(1+0.00367t)](h/760)$, the weight of a liter of dry air at 20 deg. cent. and a pressure of 760 mm. of mercury (at 0 deg. cent.) is 1.2046 g.; t is in deg. cent. and h in mm. of mercury at 0 deg. cent. (Bureau of Standards). The following table gives the weight in grams per liter of dry air containing 0.04 per cent. of CO_2 (Bur. of Stds.).

Temp. in deg. cent.	Barometer, in mm. (0 deg. cent., standard gravity)					
	720	730	740	750	760	770
15	1.1611	1.1772	1.1933	1.2095	1.2256	1.2417
20	1.1412	1.1571	1.1729	1.1888	1.2046	1.2205
25	1.1220	1.1376	1.1532	1.1688	1.1844	1.2001
30	1.1035	1.1188	1.1342	1.1495	1.1648	1.1800

437. The specific heat of air. Regnault's mean value of the specific heat of air at constant pressure is 0.2375; nitrogen 0.2438; oxygen, 0.2175; hydrogen, 3.409. Taking into account the temperature, the specific heat of air at constant pressure is

$$C = 0.24112 + 0.000009t \qquad (24)$$

where C is expressed in B.t.u. per lb. and t is in deg. fahr.

* Greene, A. M. Jr. "The Elements of Heating and Ventilation;" John Wiley & Sons, New York, 1913; Chap. II.

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SECTION 5

MAGNETS, INDUCTION COILS, CONDENSERS AND RESISTORS

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SECTION 5

MAGNETS

BY CHARLES R. UNDERHILL

GENERAL

1. A magnet is a body which possesses the property of attracting magnetic substances. All magnets may be divided into two classes, *i.e.*, permanent magnets and electromagnets.

2. A permanent magnet is one which retains a nearly constant value of m.m.f. for an indefinite period. The permanent magnets used in practice are made of hardened steel and are magnetized by placing them in a strong magnetic field.

3. An electromagnet or temporary magnet is one in which the magnetic field is produced by an electric current. In its simplest form, it consists of a helix of conducting material which, when energized by an electric current, possesses many of the magnetic-field characteristics of a permanent magnet. Since soft iron is capable of being magnetized to a high degree and retains very little permanent magnetism, with the result that the magnetic field may be varied in great degree by regulating the strength of the current, electromagnets are usually provided with soft-iron **cores.**

PERMANENT MAGNETS

4. Permanent magnets are used where a constant field is desired, as in electrical instruments, magneto-generators, etc. In order to retain its strength, a permanent magnet should have as short an air-gap as possible and the ratio of its length to its cross-sectional area should be great. Unless proper precautions are taken, the steel is likely to crack and warp in hardening.

5. Permanent magnets lose a portion of their original magnetism when used for a long time, so that they become what is termed aged. Those used in instruments, magnetos, etc., are **artificially aged** in the process of manufacture. This is accomplished in various ways. One method of aging magnets for watt-hour meters is to pass them several times through a bath of boiling water or oil and then to demagnetise them to about 75 per cent. of the original value by rotating a copper disc between the poles. Another method is to place a large number of magnets parallel to each other, with a copper strip between the poles, and then to demagnetise them by passing a strong current through the strip. (Also see Par. **16.**)

6. Permanent magnets are made from the best grade of crucible tungsten steel which contains about 5 per cent. of tungsten, a small percentage each of chromium and manganese, and from 0.63 to 0.66 per cent. carbon. Domestic steel of this variety is found to be equal to or better than any imported magnet steel.

7. Details of manufacture. The practice of the Sangamo Electric Co. is as follows: After preliminary tests, the steel bars are sheared cold and then heated in a special fuel-oil furnace so arranged that the products of combustion do not come directly in contact with the steel. The pieces are forged at a bright red heat, in a large press, using but one heat if possible. A vertical type press is preferred to the "bull-dozer" type. The pieces are then allowed to cool in the air, if no drilling is required; or, if drilling is necessary, they are packed in mica dust to prevent air-hardening, which takes place to a certain extent even with steel containing no more than

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5 per cent. of tungsten. The pieces are then ground to dimensions, tumbled to remove all scale, and heated in a fuel-oil furnace, arranged with a recording pyrometer for checking the temperature. The next operation is the hardening or tempering.

8. **The hardening process** is carried on in a darkened room so that the operator can judge the heat, aside from the information obtained from the pyrometer. The pieces are brought to a temperature of 840 deg. to 860 deg. cent., the proper temperature varying according to the carbon content, and are quenched in pure running water at a temperature varying from 40 deg. fahr. in winter, to 70 deg. fahr. in summer. During hardening the pieces are held in special tongs or clamps to prevent springing; they are again tumbled to remove all scale, and then given any final finish grinding that may be required.

9. **Magnetizing process.** The pieces are magnetized by placing them in special jaws which form the pole pieces of a powerful electromagnet, and sufficient current is then switched on, for a brief period, to force the maximum magnetic flux through them.

10. **Artificial aging.** The magnets are artificially aged by placing them in oil and heating to a temperature of 250 deg. fahr. for about one-half hour, after which they are placed on a vibrating or humming device for vibration aging; the latter treatment reduces the strength of the magnet, but not so much as the heat aging. (Also see Par. 5.)

11. **Precautions in handling.** After being japanned, the magnets are tested for field strength and laid away in a tray. In handling, precautions should be taken to prevent undue throwing about after magnetizing and aging; but, unless the magnet has a long air-gap, it is found that no particular care is necessary to prevent further loss in strength. In case a magnet has a long air-gap, as in magneto field magnets, a **keeper** is placed across the poles.

ELECTROMAGNETS

12. **A continuous-current electromagnet** is one which is designed for operation from continuous-current circuits. In this class, the **effects of inductance** are noticeable only when the magnet is switched in or out of circuit and while it is doing work.

13. **An alternating-current electromagnet** is one which is designed for operation from alternating-current circuits. In this case the magnitude and the direction of the current are varying periodically; hence the effects of inductance are so great as to require the design of the coil and other parts to be radically different from those for continuous-current circuits, although the laws governing the pulls are similar.

14. **Uses.** There are so many uses for electromagnets that it would be a considerable task to enumerate them all, but in most cases their uses are familiar. They are being used in increasing quantities in the electrical control of machines wherein mechanical devices were formerly employed. In general, they may be divided into two classes.

15. **A portative electromagnet** is one designed for holding or lifting only; that is, it is merely intended to grip and hold in place material brought in contact with it.

16. **A tractive electromagnet** is one designed to pull a load through a distance and thus do work.

TYPES OF ELECTROMAGNETS

17. **A solenoid** is a winding of insulated conductor consisting of a series of superimposed helices of right and left pitch. It is the basis of all of the common forms of electromagnets.

18. **A solenoid-and-plunger** is a solenoid mounted on a suitable non-magnetic bobbin or spool and provided with a movable bar of soft iron or steel called a plunger. When the coil is energized, the plunger becomes magnetized by the influence of the magnetic flux from the current in the coil, and mutual attraction then takes place between the coil and the plunger. If the force of attraction is great enough to overcome the load, the plunger will advance into the coil until their magnetic centers coincide, and thereafter no more work can be done unless the relative positions of the coil and the plunger are again changed by external means.

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19. An iron-clad solenoid is a solenoid-and-plunger provided with an iron or steel frame or jacket. The effect is to confine the magnetic field within the limits of the frame. When provided with a stop, as in Fig. 1, this type is commonly known as a **plunger electromagnet.**



FIG. 1.—Plunger electromagnet.

20. A bar electromagnet is a solenoid-and-plunger with the plunger inserted in the solenoid and rigidly fixed in position.

21. A horseshoe electromagnet is a bar electromagnet bent into U form in order to bring the pole ends near together. The practical type consists of two bar electromagnets magnetically joined together at one end by means of a **yoke** or **backiron.** Both coils are usually wound in the same direction and their inside wires connected together. The **armature** consists of a piece of soft iron or steel of sufficient length to bridge the gap from pole to pole, and of cross-section great enough to conduct the flux economically.

22. An iron-clad electromagnet is a bar electromagnet inserted in a soft-iron or steel cup, so that the rim of the cup and the core of the electromagnet form the attracting surfaces (or poles) for the armature, which usually consists of a disc of soft iron or steel.

23. Modified types. There are many modifications of the above fundamental types. For instance, plunger electromagnets are sometimes made in the horseshoe form, and a modification of the horseshoe electromagnet will be recognised in the iron-clad electromagnet. In some telephone relays, an angle-iron is employed instead of the shell or cup.

GENERAL THEORY OF ELECTROMAGNETS

24. Maxwell's fundamental equation for the pull applies strictly to a portative electromagnet consisting of a bar electromagnet separated at its middle and having a hypothetically zero air-gap, so that no flux can leak back from the abutting ends of the half-cores to their opposite ends. The equation for the pull in dynes per sq. cm. is $P = \mathfrak{B}^2/8\pi$. But $\mathfrak{B} = 4\pi\mathfrak{I} + \mathfrak{H}$, wherein $\mathfrak{I}$ is the intensity of magnetisation in the iron only. It is convenient to reduce $4\pi\mathfrak{I}$ to ϕ_i/s, and $\mathfrak{H}$ to ϕ_a/s, wherein ϕ_i is the iron flux, equivalent to the flux in a permanent magnet; ϕ_a is the flux in the air-core only, and s is the cross-sectional area of the core in square centimeters. Then

$$\mathfrak{B} = \frac{\phi_i + \phi_a}{s} \qquad \text{(gausses)} \qquad (1)$$

$$\text{whence } P = \frac{\phi_i^2 + 2\phi_i\phi_a + \phi_a^2}{8\pi s^2} \qquad \text{(dynes per sq. cm.)} \qquad (2)$$

25. Theoretical components of pull. Conventionally stated, $\phi_i^2/8\pi s^2$ is the purely magnetic pull between the two half-cores; $2\phi_i\phi_a/8\pi s^2$ is the pull due to the "solenoid effect" between the half-coils and the half-cores; and $\phi_a^2/8\pi s^2$ is the pull between the half-coils, which cannot be utilized in practical electromagnets with solidly wound coils. The actual pull, in dynes per square centimeter, for such a portative electromagnet, *i.e.*, when there is no appreciable air-gap between the attracting surfaces of the half-cores, and the coil is solidly wound, is

$$P = \frac{\phi_i^2 + 2\phi_i\phi_a}{8\pi s^2} \qquad \text{(dynes per sq. cm.)} \qquad (3)$$

26. Total pull between two polar surfaces. An electromagnet can do work only when there is an air-gap. The longitudinal contraction of the flux in the air-gap of a tractive electromagnet causes the pull. The pull in dynes per square centimeter between the polar surfaces of the cores of a horseshoe electromagnet and its armature, or for any other type of electromagnet with the coils and cores rigidly fixed, relatively, is $P = \phi_g^2/8\pi s^2$, wherein ϕ_g is the total average flux producing the pull. This equation expresses the pull in an air-gap, or the pull between two magnetic masses in contact, and holds for permanent magnets.

27. The pull due to an iron-clad solenoid or a plunger electromagnet consists of two components, since there are two magnetic circuits in shunt

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with one another. One of these circuits is through the air-gap, and this pull, in dynes per square centimeter, is equal to $\phi_g^2/8\pi s^2$. The other circuit is the **leakage circuit** from the inner end of the plunger (Fig. 1), through the coil and frame, back to the place where the plunger enters the coil. Hence the pull, in dynes per square centimeter, is

$$P = \frac{\phi_g^2 + 2\phi_l\phi_g}{8\pi s^2} \qquad \text{(dynes per sq. cm.)} \qquad (4)$$

When the air-gap is relatively long, the value of ϕ_l is generally greatly in excess of that of ϕ_g, since the reluctance of the leakage circuit is usually lower than that of the air-gap.

28. The useful work performed by an electromagnet is generally defined as initial pull times range or distance of travel. It has been theoretically proven that the **maximum amount of work** may be obtained from an electromagnet when the reluctance of the working air-gap is equa to that of the rest of the magnetic circuit* (Fig. 2). This is true for electromagnets with their coils and cores rigidly fixed, relatively, but is not true for electromagnets with movable plungers, especially when the air-gaps are long and the m.m.fs. are of high value, owing to the "solenoid effect." However, the rule holds for all types of electromagnets so far as the air-gap, only, is concerned. (See Par. 62.)

29. The maximum work in the air-gap (initial pull × distance) is obtained when $\mathcal{F}_g\phi_g$, that is, the product of the air-gap m.m.f. and the flux, becomes a maximum. The expression for $\mathcal{F}_g$ is

$$\mathcal{F}_g = \left(\frac{\mathcal{R}_g}{\mathcal{R}_g + \mathcal{R}_i}\right)\mathcal{F}_t \qquad \text{(gilberts)} \qquad (5)$$

wherein $\mathcal{F}_g$ is the air-gap m.m.f., $\mathcal{R}_g$ the reluctance of the working air-gap, $\mathcal{R}_i$ the reluctance of the magnetic circuit exclusive of the working air-gap, and $\mathcal{F}_t$ the total m.m.f. The reluctance of the air-gap is $\mathcal{R}_g = \mathcal{F}_g/\phi_g$. The general theoretical air-gap characteristics are shown in Fig. 2. This is similar to the rule for the maximum wattage which may be obtained in a coil connected in series with a continuous-current line of constant e.m.f. As is well known, the maximum wattage is obtainable when the resistance of the coil is equal to the sum of all of the other resistances in series in the line. Likewise, when the proper length of the air-gap is either increased or diminished, the maximum pull × length of air-gap is diminished.

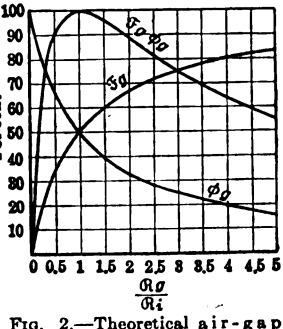


FIG. 2.—Theoretical air-gap characteristics showing conditions for maximum work (pull × distance).

30. Electrical time-constant. When quick action is desired, it is necessary that the current reach its maximum value as soon as possible. Referring to Sec. 2, it will be seen that a definite time interval, in each case, is required for the current to reach its maximum value. The relationship between the instantaneous current, the constant impressed e.m.f. and the constants of the circuit is expressed by Helmholtz's law (Sec. 2) thus

$$i = \frac{E}{R}\left(1 - \epsilon^{-\frac{R_t}{L}}\right) \qquad \text{(amp.)} \qquad (6)$$

wherein i is the instantaneous value of the current, E the e.m.f. in volts impressed upon the magnet winding, R the resistance in ohms of the winding, ϵ the base of the Naperian logarithm system ($\epsilon = 2.71828$), L the in-

* Carichoff E. R. "On the Design of Electromagnets for Specific Duty;" *Electrical World*, 1894, Vol. XXIII, pp. 113 and 212.

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ductance (Par. 31) in henrys, and t the elapsed time in seconds from the moment the circuit was closed. Solving the above equation for t,

$$t = -\frac{L}{R} \log_e \left(1 - \frac{R_i}{E}\right) \qquad \text{(sec.)} \qquad (7)$$

wherein L/R is called the time-constant. From this it is seen that for a given ratio of instantaneous current to the Ohm's law or steady current the time-constant is the only factor which determines the time required to establish it. The time-constant is fixed by the magnetic circuit and by the ampere-turns (when iron is present), and is independent of the number of turns, since both the resistance and the inductance vary as the square of the number of turns, for a given winding volume.

31. The approximate inductance of a magnet, in which the air-gap is not very long, can be found by assuming the magnet to be connected to a source of alternating e.m.f., of known frequency and having a sine-wave form. Let l_i be the length in cm. of the iron circuit; l_a the length in centimeters of the air-gap; N the number of turns; s the cross-sectional area in square centimeters of the magnetic circuit, and ϕ the maximum value of the total flux. Then the alternating e.m.f. which must be impressed upon the winding to produce a maximum flux ϕ, is

$$E = 4.44 f N \phi 10^{-8} \qquad \text{(volts, effective)} \qquad (8)$$

where f is the frequency in cycles per second. The approximate reluctance is,

$$\mathfrak{R} = \frac{1}{s}\left(\frac{l_i}{\mu} + l_a\right) \qquad \text{(oersteds)} \qquad (9)$$

μ can be taken from curves in Sec. 4. The m.m.f. is $\mathfrak{F} = 1.257NI$ wherein I is the effective (root mean square) current in amperes. It follows from $\mathfrak{F} = \phi\mathfrak{R}$ that

$$I = \frac{\phi\mathfrak{R}}{1.257N} \qquad \text{(amp.)} \qquad (10)$$

and then

$$L = \frac{E}{2\pi f I} \qquad \text{(henrys)} \qquad (11)$$

32. Effect of movable plunger. Magnets with movable plungers which are designed for quick and powerful action require careful study of the initial conditions. At the first instant, the value of the current increases at such a rate that the flux interlinked with the winding will generate a counter-e.m.f. equal to the impressed e.m.f. The pull produced by the flux due to this current will start the plunger, and the sudden decrease in reluctance due to the closing of the air-gap will produce a corresponding increase in flux and thus decrease the rate of change of the current, that is, the current will be retarded in reaching its final and permanent value. Because of this phenomenon it is usual to design such magnets (for instance, those used on automatic starters) for a much lower impressed e.m.f. than is actually used at the start; in order then to protect the winding, a higher resistance is automatically inserted in series with it at the moment the plunger arrives at the end of its stroke. This resistance limits the current to that value necessary to maintain the required final pull on the plunger.

33. The action of the plunger in reducing the reluctance of the magnetic circuit may be approached from the energy standpoint; thus, the total energy which is supplied to the magnetic field up to any instant is

$$W = E\int_0^t i\,dt = \frac{i^2 L}{2} + 0.113Fl \qquad \text{(watt-seconds)} \qquad (12)$$

wherein i is the instantaneous value of the current in amperes, L the instantaneous value of the inductance in henrys, F the average pull on the plunger in pounds, and l the distance traveled in inches.

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34. Current-time curves for plunger electromagnets. Referring to Fig. 3, the current-time curves* for a certain magnet are plotted for different stationary positions of the plunger, each curve representing a given air-gap. If the plunger moves forward before the current has reached its final and permanent value, the reluctance decreases and the current drops

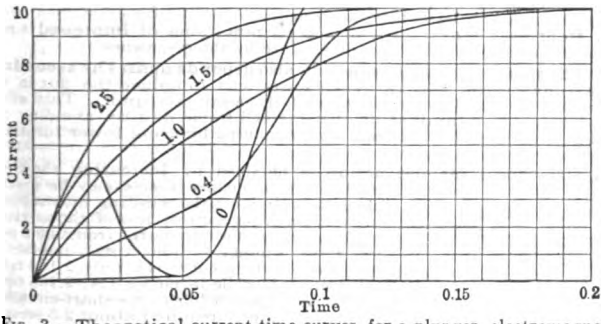


FIG. 3.—Theoretical current-time curves for a plunger electromagnet.

from one curve to the next, corresponding at each instant with the air-gap and the time. If, for instance, after 0.02 sec. the plunger closes the air-gap to 1.5 cm., it is probable that the current will have the same value as though it had increased from zero along the curve corresponding to the air-gap 1.5 cm., and it cannot have a greater value. In Fig. 4, the current-time curves are given for maximum and zero air-gaps; assuming the current to increase along the first curve until *a* is reached, before the pull becomes sufficient to overcome the friction and start the plunger, the latter then moves forward with a rapidly increasing acceleration to the end where the air-gap is zero, and thereafter the current follows the curve corresponding to the zero air-gap to *b*, where the magnetic circuit becomes saturated and the current rises rapidly to the value determined by the resistance of the winding. If an external resistance be inserted by means of a short-circuiting switch actuated by the plunger, the current may be limited to any desired value.

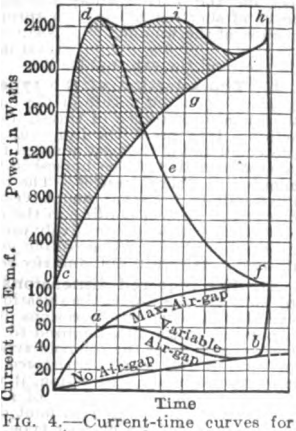


FIG. 4.—Current-time curves for maximum and zero air-gaps.

35. Energy stored in the magnetic circuit. The current curves in Fig. 4 can also be chosen to represent the *ir* drop in the winding; then the difference between the final value I_{max}, and the instantaneous value *i*, represents the counter-e.m.f. of inductance, that is, the counter-e.m.f. generated by the flux cutting the turns of the winding. The counter-e.m.f. of inductance multiplied by the current in the winding is the **power supplied to the magnetic circuit.** These power curves are plotted above the current curves in Fig. 4. Curve *cdef* is the power curve for the maximum air-gap; *cghf* is that for zero air-gap, and *cdihf* that for the varying air-gap. The areas under these

*Calculated and plotted by Mr. O. A. Kenyon; 3rd edition, Standard Handbook.

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curves represent the energy transferred to the magnetic field, in each case. With the moving plunger, the total energy input to the magnetic field is the area *cdihf*, while that left as stored energy at the end of the stroke and which must be dissipated when the circuit is broken is the area *cghf*. The difference between these two, *cdihg* (cross-hatched) represents the energy transformed into mechanical work and dissipated by friction and impact of the plunger during its travel, iron losses being neglected.

36. Impressed e.m.f. The final permanent value of impressed e.m.f. in continuous-current magnets is determined by the resistance.

37. The speed of the magnet action also depends upon the secondary losses (eddy currents, Sec. 2). These losses tend to reduce the flux in the core and thus retard the attainment of the maximum pull. This effect can be reduced by **laminating** the core and frame and by avoiding the use of a metallic bobbin. It can also be reduced by using fewer turns and larger current.

38. Slow-speed magnet action is obtained by increasing the time-constant and the secondary losses. The secondary losses can be greatly increased by dividing the winding into sections and short-circuiting more or less of the sections. Fig. 5 shows the effect of short-circuiting a portion of the winding.* The total number of turns was 8,400; in curve (1), only 2,165 turns were energized, while in curve (2), 2,165 turns were energized and 6,235 turns short-circuited. In the first case it required about 2.5 seconds to reach the maximum current, while in the second case, 4 seconds were required.

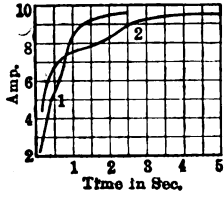


FIG. 5.—Showing the effect on the current-time curve of short-circuiting a portion of the winding.

39. Inertia of moving system. When the speed of action is an important factor, the inertia of the load to be moved must be considered. For the same pull and range, a quicker action will be obtained in overcoming the tension of a spring than in moving a mass whose weight is equivalent to the tension of the spring. The total mass to be moved is the sum of that of the plunger and the external load.

40. The selection of the type of electromagnet for specific work depends upon the nature of the e.m.f. (whether continuous or alternating) the range or distance of travel, and the rate of travel or the quickness of action. In general, the iron-clad solenoid type is mechanically the better protected and is the best adapted for a long range and a strong pull, but it is slow in action. The horseshoe type has the quicker action, but is only adapted for short ranges. The plunger-electromagnet type has an action intermediate between the above-mentioned types and may approximate one or the other according to the range and the dimensions of the plunger. The clapper type is extensively used on control apparatus, since it acts very quickly and has a strong *sealing pull*. The general rule is that what is lost in time is gained in pull and *vice versa*.

41. The required dimensions of an electromagnet are proportional to the load, the range, the duration of excitation and the interval between excitations. The cross-sections of the plungers, cores and frames will depend upon the flux required to produce the desired pull. In long-range electromagnets of the solenoid type, wherein the pull is proportional to the product of the magnetizing force and the flux in the plunger, the plunger may be of small cross-section, if the duration of excitation is to be brief, since the magnetizing force of a comparatively small coil may be made great for a short period without danger of injury from overheating. This does not hold for a clapper type, since the main pull is dependent upon the flux which the cores are able to conduct, and is only slightly affected by an increase in the magnetizing force after the cores approach saturation.

42. Electromagnets designed for continuous service must have windings of such volume and radiating surface, and wires of such cross-section

*Lindquist, D. L. "Alternating-current Magnets;" *Electrical World*, 1906, Vol. XLVII, p. 1295.

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that the coils will not become overheated, but the proper pull will be maintained even after the winding has been in circuit continuously for many hours. The designer should allow too much space, rather than too little, for the winding and the insulation of the coil, because, while the coil may be relatively small for intermittent service, it is often found necessary or desirable to leave the coil in circuit longer than originally intended.

43. **The air-gap pull** of any electromagnet is

$$F' = \frac{\mathfrak{B}'^2 s'}{72{,}130{,}000} \quad \text{(lb.)} \qquad (13)$$

or

$$F = \frac{\mathfrak{B}^2 s}{8\pi \times 981{,}000} \quad \text{(kg.)} \qquad (14)$$

where $\mathfrak{B}'$ and $\mathfrak{B}$ are the flux densities in maxwells per square inch and per square centimeter respectively; s' and s are the cross-sectional area of the core or plunger in square inches and square centimeters respectively.

44. **Curves plotted between the pull per unit area of core and the flux density** are shown in Fig. 6. The pull is plotted with maxwells per square centimeter, but maxwells per square centimeter are also plotted with maxwells per square inch so that pull can be read off for either one.

45. **Relation between pull and air-gap.** In designing magnets, an approximate idea of the

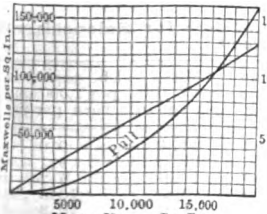


FIG. 6.—Curve showing relationship between the pull per unit area of core and the flux density.

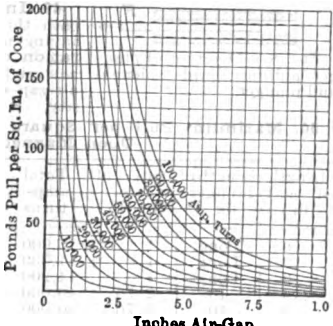


FIG. 7.—Curves showing relation between the pull in lb. per sq. in. and the air-gap for different amp-turns.

principal dimensions and proportions can be found from the curves given in Fig. 7, which show the relation between the pull in pounds per square inch and the air-gap for different numbers of ampere-turns.

CONTINUOUS-CURRENT TRACTIVE ELECTROMAGNETS FOR LONG RANGE

46. **Solenoids** with plungers only, *i.e.*, without an iron frame, are seldom used in practice except in cases where it is desired to take advantage of the peculiar pull characteristics. However, it is important to understand their actions since the design of all movable-core electromagnets is influenced by the characteristics of the simple coil-and-plunger.

47. **The magnetizing force of a solenoid** is a maximum at its centre, falling off to about one-half of the maximum at each end of the winding. When one end of the plunger is placed in or near the end of the solenoid it becomes magnetized, and mutual attraction results between the flux in the plunger and the magnetizing force due to the ampere-turns in the winding of the solenoid. The plunger becomes more and more saturated as it enters the solenoid, and, in case the plunger is not much longer than the solenoid, all tractive effort ceases when the respective magnetic centres of the solenoid and the plunger coincide. As a result, the maximum pull always occurs after the inserted end of the plunger has passed the middle of the solenoid, although, in cases of long solenoids and where the magnetiz-

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ing force has a high value as compared with the cross-sectional area of the plunger, the maximum pull may occur for a considerable distance on each side of the middle of the solenoid. On the other hand, with very short solenoids, the maximum pull may occur at or near the end of the solenoid opposite to that at which the plunger enters.

48. Characteristic pull with solenoid and plunger. Fig. 8 shows the approximate pull diagram for different positions of the plunger. The expression for the maximum uniform pull is

$$F = Cs\frac{NI}{l} \qquad \text{(lb.)} \qquad (15)$$

where I is the current in amp., N the number of turns, s the cross-sectional area of the core or plunger in square inches, l the length of the solenoid in inches and C the pull in pound per square inch per ampere-turn per inch. C depends upon the proportions of the coil, the degree of saturation, and the length, physical character and chemical purity of the plunger. Par. **50** gives values for C for various solenoids tested by the author.

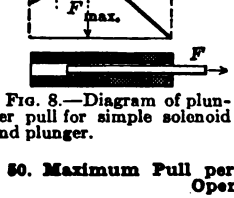


FIG. 8.—Diagram of plunger pull for simple solenoid and plunger.

49. In magnets with long air-gaps, the path through the iron can be considered as having no reluctance. Therefore the **saturation characteristic** can be assumed to be a straight line, and the ampere-turns for the air-gap directly proportional to the flux density.

50. Maximum Pull per Square Inch of Core for Solenoids with Open Magnetic Circuit*

Length of coil (in.)	Length of plunger (in.)	Area of core (sq. in.)	Total amp-turns	Amp-turns per in.	Max. pull, lb. per sq. in	Lb. per sq. in. per 1,000 amp-turn per in.
6	Long	1	15,000	2,500	22.4	9.0
9	Long	1	11,330	1,260	11.5	9.1
9	Long	1	14,200	1,580	14.6	9.2
10	10	2.76	40,000	4,000	40.2	10.0
10	10	2.76	60,000	6,000	61.6	10.3
10	10	2.76	80,000	8,000	80.8	10.1
12	Long	1	11,200	930	8.75	9.4
12	Long	1	20,500	1,710	16.75	9.8
18	36	1	18,200	1,010	9.8	9.7
18	36	1	41,000	2,280	22.5	9.8
18	18	1	18,200	1,010	9.8	9.7
18	18	1	41,000	2,280	22.5	9.8

NOTE.—These tests indicate that little is gained in maximum pull by making the plunger considerably longer than the coil.

51. The diameter of the coil should be about three times that of the plunger, and the **length of the coil** should be at least two or three times its outside diameter whenever possible.

52. The range is directly proportional to the length of the coil, regardless of the ampere-turns.

53. The pull in an iron-clad solenoid, with or without a stop, is composed of two components; one is the pull between the end of the stop or frame and the plunger, and the other is that between the winding and the plunger. The latter is all important at the beginning of the stroke, but near the end the stop-pull becomes predominant. The expression for the pull is

$$F = s\left(\frac{NI}{l_a c}\right)^2 + \frac{sCNI}{l} = sNI\left[\frac{NI}{l_a^2 c^2} + \frac{C}{l}\right] \qquad \text{(lb.)} \qquad (16)$$

* Underhill, C. R. "The Practical Design of the Solenoid;" *Electrical World and Engineer*, 1905, Vol. XLV, p. 796.

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where s is the cross-sectional area of the core in square inches, I the current in amp., N the number of turns, l_a the length of the air gap in inches, l the length of the coil in inches, and c and C constants, which depend on the proportions of the magnet, the materials used and the degree of saturation. Approximate values for ordinary soft-iron cores are $c = 2{,}600$; for lengths of coil greater than 10 times the diameter of the plunger, $C = 0.0096$ (see Par. 50 for values of 1,000 C).

54. Formula for pull characteristic. Referring to the pull diagram (Fig. 8), it will be seen that the solenoid pull is assumed to decrease as a straight-line function, commencing at a point about $0.4l$ from the end of the coil.* From this point on the total pull due to the plunger electromagnet can be expressed thus:

$$F = sNI\left[\frac{NI}{l_a{}^2c^2} + \frac{l'c}{0.4l^2}\right] \quad \text{(lb.)} \qquad (17)$$

wherein l' is the distance in inches which the plunger is inserted in the coil. The constants are the same as those given in Par. 53.

55. Test data on pull characteristics. Fig. 9 shows curves from actual test.* Curve (1) is that of a simple coil-and-plunger; (2) that of a coil-and-plunger with stop; (3), that of an iron-clad coil-and-plunger; (4) and (5) show the same iron-clad coil with different lengths of stop. All these curves were made with the same coil, which was 12 in. long and had a total of 10,000 amp-turns, or 834 amp-turns per linear inch.

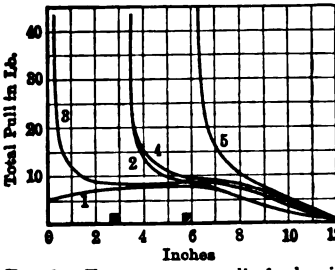


FIG. 9.—Test curves on pull of solenoid and plunger.

56. Analysis of test data (Par. 55). Referring to Fig. 9, the pull with the iron-clad magnet, curve (4), corresponding to the position 5 ($l_a = 2$ in.) of the plunger, is 10.75 lb., approximately. Referring to Par. 49, the pull due to the coil alone is about 9.7 lb. per square inch, per 1,000 amp-turns per inch, or $9.7 \times 0.834 = 8.1$ lb. Next referring to Fig. 7, it is found that corresponding to $l_a = 2$ in., and 10,000 amp-turns, the pull is about 2.5 lb. per square inch; adding $8.1 + 2.5 = 10.6$ lb., which is a sufficiently close check for all practical purposes.

CONTINUOUS-CURRENT TRACTIVE ELECTROMAGNETS FOR SHORT RANGE

57. Test data on pull characteristics of horseshoe type of electromagnet. Fig. 10 shows the test characteristics of the horseshoe electromagnet in Fig. 11.† These curves should be compared with those in Fig. 7.

58. Test data on pull characteristics of clapper type of electromagnet. One of the modifications of a horseshoe electromagnet is the clapper type shown in Fig. 12. Fig. 13 shows the test characteristics of this magnet, as determined by the Cutler-Hammer Mfg. Co. The cylindrical surface of this magnet is approximately 25 sq. in.

59. Electromagnets used in railway signal apparatus must respond to very slight changes in current strength. For instance, a 4-ohm **track relay**, operating on an e.m.f. of 1 volt, must attract its armature with sufficient force to close four contacts with a current of 75 milliamp. and the armature must drop away when the current passing through the coils is reduced to 40 milliamp. A minimum air-gap of $\frac{1}{64}$ in. is maintained between the poles of the magnet and the armature, by means of stop pins of non-

* Underhill, C. R. "The Law of the Plunger Electromagnet;" *Electrical World and Engineer*, 1905, Vol. XLV, p. 934.

† Underhill, C. R. "The Performances of Different Types of Electromagnets;" *American Electrician*, 1905, Vol. LVII, p. 299.

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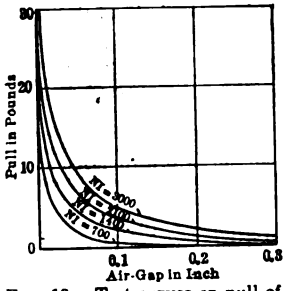


FIG. 10.—Test curves on pull of horseshoe electromagnet.

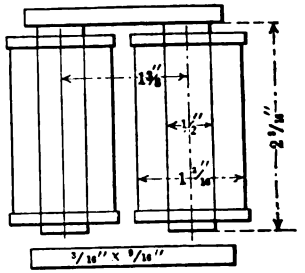


FIG. 11.—Horseshoe type of electromagnet.

magnetic material located in the armature directly under the centre of the magnet cores. The total amp-turns, with 0.075 amp., are 127.5; the cores are ⅜ in. in diameter, and each spool is 4 in. long by 2 in. in diameter. In general, signal relays are required to release their armatures when the energising current is reduced one-half.

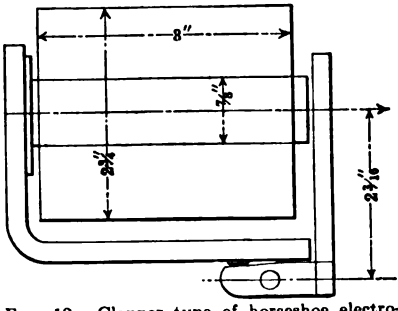


FIG. 12.—Clapper type of horseshoe electromagnet.

60. Electromagnets for telegraph and telephone service, like those for signal apparatus, are designed to perform the sole function of closing or opening one or more local contacts which control other circuits and apparatus. The armatures of these magnets customarily work through very limited ranges, not exceeding as a rule a very small fraction of an inch; the opposing force is sometimes gravity, sometimes a light spring. Such relays are also wound differentially for certain kinds of work, and sometimes are polarized (having a permanently magnetized steel core) in order to respond only to currents flowing in a given predetermined direction around the windings (see Sec. 21).

61. The equation for the pull due to electromagnets of the horseshoe type is given by

$$F = s\left(\frac{NI}{l_a c}\right)^2 \quad \text{(lb.)} \qquad (18)$$

where the constants are the same as those given in Par. 53. The total length of all the air-gaps is to be taken for l_a. The equation is only approximately correct, in this case, owing to leakage. It is better to increase the

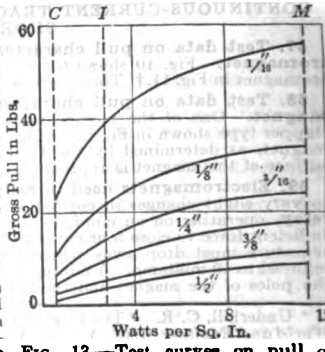


FIG. 13.—Test curves on pull of clapper type of electromagnet.

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ampere-turns about 50 per cent. to allow for leakage, depending upon the length of the air-gaps.

CONDITIONS FOR MAXIMUM WORK

62. The work in the air-gap (pull × distance) of a magnet becomes a maximum when the air-gap reluctance is equal to that of the rest of the circuit (Par. 29). In Fig. 14, F_s is the solenoid pull, F_g is the air-gap pull, and F_t is the total pull as ascertained by actual test* of a plunger electromag-

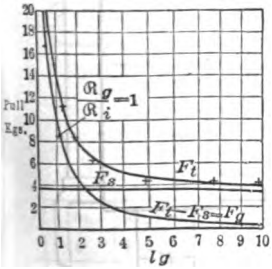


FIG. 14.—Components of pull with a plunger electromagnet.

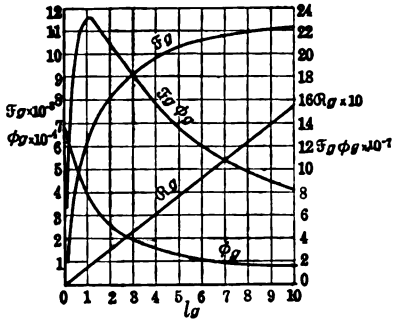


FIG. 15.—Calculated air-gap characteristics of a plunger electromagnet.

net. Fig. 15 shows the calculated air-gap characteristics which should be compared with those in Fig. 2 (Par. 29); l_g represents the length of air-gaps in centimeters. The actual work obtained in the air-gap, the work due to the coil-and-plunger, and the total work are represented by curves W_g, W_s, and W_t, respectively, in Fig. 16. It is evident that the work (pull × distance) due to a solenoid-and-plunger, or plunger electromagnet, of the character of that tested, is limited only by the length of stroke. When the solenoid pull is very weak as compared with the air-gap pull, the maximum work will fall between these two extremes. In general, electromagnets are designed for maximum initial pull × distance or length of stroke. Exceptions are lifting magnets and those used in electric hammers. The amount of material used to construct an electromagnet depends either upon the time it will receive electric energy after it has performed its work, the frequency at which it performs its work, or both.

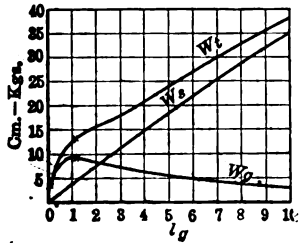


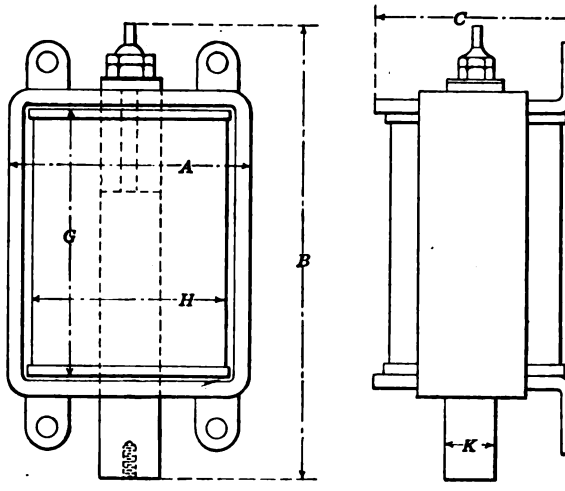
FIG. 16.—Components of work (pull × distance) performed by a plunger electromagnet.

STANDARD ELECTROMAGNETS

63. Data on standard electromagnets. The following figures, tables, and charts show the dimensions and characteristics of some standard electromagnets (The Cutler-Hammer Mfg. Co.). The curves in general represent tests with 115-volt direct-current coils. Three classes of duty are listed (see Figs. 17 to 31, inclusive).

* Underhill, C. R. "Operation of Plunger Electromagnets;" *Electrical World*, 1912, Vol. LIX, p. 1388.

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No.	Curve	A	B	C	G	H	K
3	Fig. 18	3¼″	6¼″	3″	3″	2¾″	¾″
5	Fig. 19	4⅛″	8¾″	3¾″	4¾″	3⅜″	1″

FIG. 17.—Standard type of plunger electromagnet with flat-end plunger.

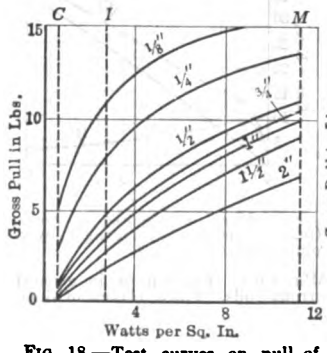


FIG. 18.—Test curves on pull of standard type of plunger electromagnet No. 3 in Fig. 17.

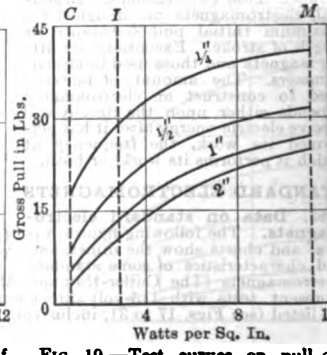
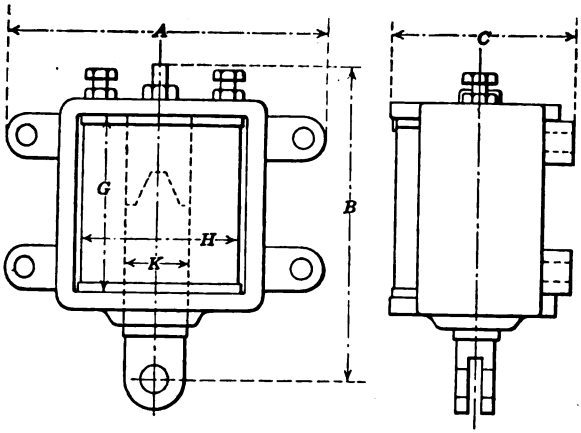


FIG. 19.—Test curves on pull of standard type of plunger electromagnet No. 5 in Fig. 17.

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No.	Curve	A	B	C	G	H	K
5	Fig. 21	6½"	8⅝"	3⅝"	4¾"	3⅜"	1"
6	Fig. 22	7"	11⅛"	3⅝"	6⅛"	3⅜"	1 3/16"
6	Fig. 23	Same Dimensions But Square End					
22	Fig. 24	9¾"	10⅞"	5⅛"	6⅛"	5⅛"	1 15/16"
23	Fig. 25	11"	12¼"	5⅞"	7⅛"	5⅝"	2 41/64"
26	Fig. 26	19"		9½"	10⅝"	8⅞"	5 15/16"

FIG. 20.—Standard type of plunger electromagnet with conical plunger and stop; also with flat-end plunger and stop.

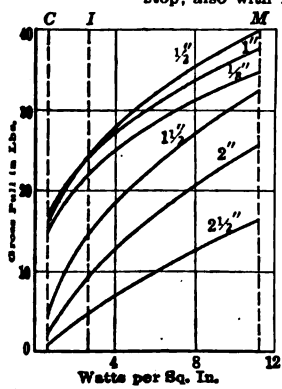


FIG. 21.—Test curves on pull of standard type of plunger electromagnet No. 5 in Fig. 20.

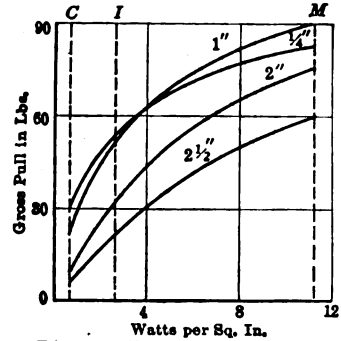


FIG. 22.—Test curves on pull of standard type of plunger electromagnet No. 6 in Fig. 20.

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64. Continuous-duty electromagnets may be excited at full voltage continuously without dangerous heating of the coils, but the pull becomes somewhat reduced when the windings reach full temperature, due to the increased resistance in the coil.

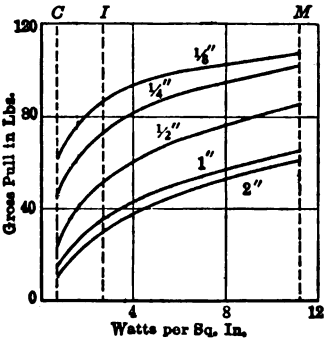


FIG. 23.—Test curves on pull of standard type of plunger electromagnet No. 6 in Fig. 20.

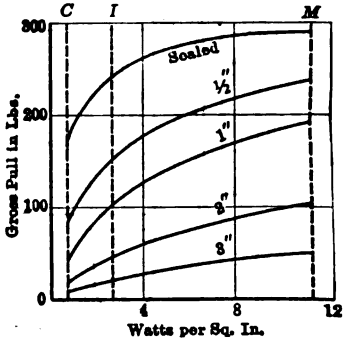


FIG. 24.—Test curves on pull of standard type of plunger electromagnet No. 22 in Fig. 20.

65. Intermittent duty is an arbitrary rating and, in general, these magnets may be excited at full voltage for not over 7 min. during any half-hour, without dangerous heating.

66. Momentary duty is also an arbitrary rating which represents the

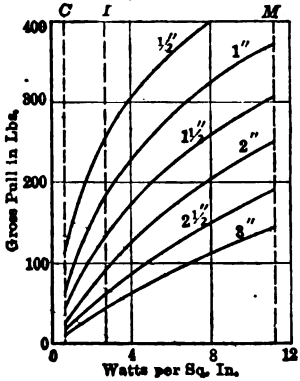


FIG. 25.—Test curves on pull of standard type of plunger electromagnet No. 23 in Fig. 20.

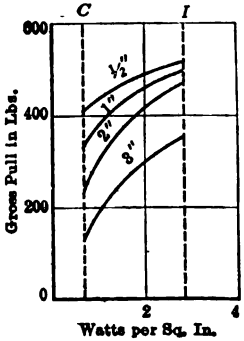


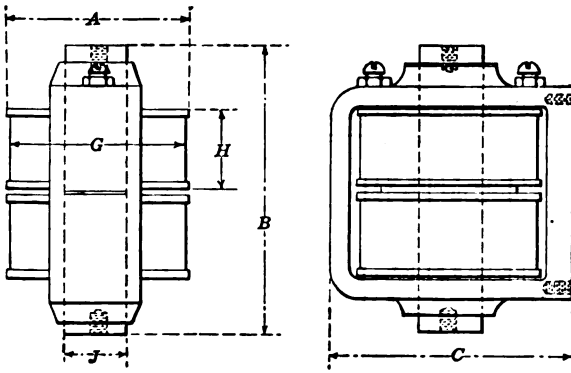
FIG. 26.—Test curves on pull of standard type of plunger electromagnet No. 26 in Fig. 20.

highest practicable rating of these magnets, and full voltage should not be maintained on them for more than 2 min. during any half-hour.

67. Protected coils have a resistance which is cut into circuit by the action of the plunger at the completion of the stroke, for the purpose of reducing the voltage at the coil terminals to a continuous-duty value.

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68. The performance curves are plotted on the basis of watts per square inch of cylindrical surface. Reference lines for the three classes of duty are given as 0.7 watts per square inch for (*C*) continuous duty; 2.8 for



No.	Curve	*A*	*B*	*C*	*G*	*H*	*J*
11	Fig.28	5¼″	11⅜″	6¾″	5⅛″	3¼″	1 $^{23}/_{32}$″
13		6¾″	12⅞″	8¾″	6⅝″	3½″	2 $^{5}/_{16}$″
14	Fig.29	7¾″	14⅜″	10″	7⅝″	4¼″	3″

FIG. 27.—Standard type of plunger electromagnet with flat-end plungers.

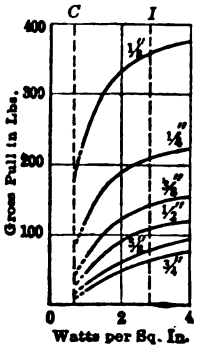


FIG. 28.—Test curves on pull of standard type of plunger electromagnet No. 11 in Fig. 27.

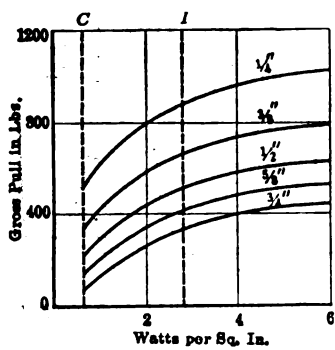


FIG. 29.—Test curves on pull of standard type of plunger electromagnet No. 14 in Fig. 27.

(*I*) intermittent duty, and 11.2 for (*M*) momentary duty. Free ventilation is assumed. (See Fig. 18, Fig. 19; Fig. 21 to Fig. 26; Fig. 28, Fig. 29 and Fig. 31.)

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69. Two forms of plungers are shown; one is conical, and the other square at the ends. The curves show the former to be preferable on most of the long-stroke types, as the tendency is to increase the starting pull and reduce the final pull. For short strokes, the square-end type is preferable.

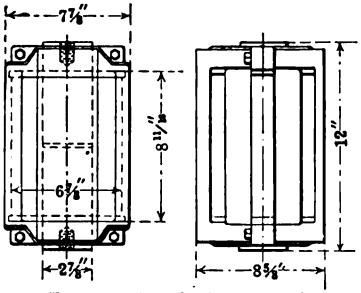


FIG. 30.—Standard type of plunger electromagnet with flat-end plungers. (See Fig. 31.)

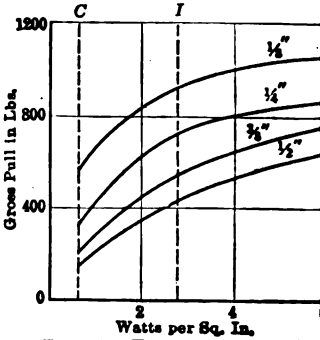


FIG. 31.—Test curves on pull standard type plunger electromagn in Fig. 30.

PORTATIVE ELECTROMAGNETS

70. Lifting magnets. Large iron-clad magnets called lifting magnets are now extensively used for the handling of materials in all branches of the iron and steel industry. They are used for handling pig iron, scrap, castings, billets, tubes, rails, plates and crop ends; for loading and unloading cars and ore vessels, and for handling skull-cracker balls and miscellaneous material.

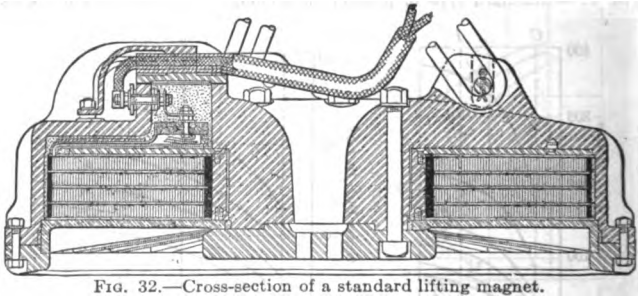


FIG. 32.—Cross-section of a standard lifting magnet.

71. Operation. All lifting magnets, of whatever make, are suitable for use on continuous-current circuits only. It is not customary to operate the magnets on very high voltages, owing to the difficulty of securing insulating material that will withstand the high inductive reaction that occurs when the circuit of a magnet is suddenly opened. Standard magnets are designed for operation on 220-volt continuous-current circuits.

72. Lifting load. It is quite impossible to calculate the load which may be lifted, owing to the varying contact of the load, but Par. **73**, giving a table published by one of the leading manufacturers, shows the approximate lifts for various magnets and materials.

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73. Dimensions, Energy Requirements and Capacities of Lifting Magnets

Magnet size	Net weight, lb.	Continuous-current energy requirements	Approximate lifting capacity in lb.	Dimensions; three-point chain suspension		Adaptation
				Head room required	Outside diameter of magnet	
18 in.	350	1.8 amp. at 220 volts	.....	12 in.	19½ in.	Handling light finished parts, also light iron or steel castings. A pair of these magnets will handle pipe up to 2-in. diameter, economically.
24 in.	750	5 amp. at 220 volts	.....	23 in.	24 in.	Similar to the 18 in. Can also handle skull-cracker balls up to 8,000 lb.
36 in.	1,800	17.5 amp. at 220 volts	800 to 1,000	42 in.	36 in.	For general service in handling pig iron, scrap, etc., where a large capacity is not required. Sometimes used with locomotive cranes.
43 in.	3,300	30 amp. at 220 volts	1,300 to 1,500	45 in.	43¾ in.	Primarily designed for use with locomotive cranes. Handles a fair average load and yet is not a heavy magnet and does not take so much energy as to cause an undue drain on the crane boiler which must supply the magnet engine-generator set.
52 in.	5,200	40 amp. at 220 volts	1,800 to 2,000	50 in.	52 in.	For general work. Used extensively in open-hearth steel plants for handling stock.
62 in.	7,500	55 amp. at 220 volts	2,400 to 2,800	56 in.	62½ in.	Used where a large tonnage must be handled. Designed as the largest magnet which can be used satisfactorily with a 5-ton crane.

With large single pieces such as castings, skull-cracker balls, etc., the lifting capacity is many times greater, becoming for example 60,000 lb. in the case of the 62-in. magnet.

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74. General construction. These magnets are very rugged in construction, as they are subject to exceedingly rough usage. The frame or body of the magnet is made, in one instance, of a special grade of dynamo steel which combines great strength and ductility with excellent magnetic qualities. They are designed to withstand heat without injury and are waterproof. Fig. 32 shows the construction of a lifting magnet made by the Cutler-Hammer Clutch Co. The Inland Steel Co. reports that about 4,000,000 lb. of machine cast pig iron were unloaded in 10.5 hr. by two 62-in. magnets. The average lift per magnet was 3,427 lb.

75. Magnetic clutches and disc brakes are of the above general class, but they attract armatures in the forms of discs. In both cases, the movements of the armatures are small. In magnetic clutches the clutch members are engaged when the magnet is energized, whereas in magnetic disc brakes, a spring presses against a disc brake when the magnet is deënergized, thus stopping rotation by means of friction.

76. Holding magnets. Portative magnets called **magnetic chucks** are extensively used for holding tools and materials in grinding and other machines. The no-load release magnet is of this type. In a general way, **magnetic separators** also belong to this class.

ALTERNATING-CURRENT TRACTIVE ELECTROMAGNETS

77. The design of an alternating-current magnet involves calculations which are essentially the same as those for an ordinary transformer. The total flux is determined by the number of turns, the supply voltage and the frequency; thus

$$E = \frac{2\pi f N \phi_{max}}{\sqrt{2}\,10^8} = 4.44 N \phi_{max}\, 10^{-8} \text{ (volts, effective)} \quad (19)$$

and

$$\phi_{max} = \frac{E\,10^8}{4.44 f N} \quad \text{(maxwells)} \quad (20)$$

where f is the frequency in cycles per second, N the number of turns, and E the impressed e.m.f. in volts.

Taking f and N as constant,

$$\phi_{max} = s\mathfrak{B}_{max} = KE \quad \text{(maxwells)} \quad (21)$$

and

$$\mathfrak{B}_{max} = K\frac{E}{s} \quad \text{(gausses)} \quad (22)$$

That is, for a given impressed e.m.f. the flux density will vary inversely as the area of the core.

78. Flux density. Since the air-gap pull varies approximately as the square of the flux density, it would appear that the flux density should be as great as possible. However, the iron losses also increase with the flux density, so that the maximum possible flux density is not the most efficient.

79. Iron losses. The major portion of the total loss takes place in the iron rather than in the copper. The **hysteresis loss** (Sec. 2) is calculated in the same way as that of a transformer, and denoted by P_h. The **eddy-current loss** (Sec. 2) is denoted by P_e. Then the total core loss is

$$P_c = P_h + P_e \quad \text{(watts)} \quad (23)$$

80. The quadrature exciting watts are expressed thus:

$$P_s = 2.5 f \frac{\phi^2_{max}}{s}\left(l_a + \frac{l_i}{\mu}\right)10^{-8} \quad \text{(watts)} \quad (24)$$

wherein l_a is the length of the air-gap in centimeters, l_i the mean length in centimeters of the magnetic circuit in the iron, and s is the cross-sectional area of the core in square centimeters. Expressing this in terms of the volume of the air-gap and of the iron, which quantities must be known in determining the core losses,

$$P_s = 2.5 f \mathfrak{B}^2_{max}\left(V_a + \frac{V_i}{\mu}\right)10^{-8} \quad \text{(watts)} \quad (25)$$

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wherein V_a and V_i are the volumes in cubic centimeters of the air-gap and the iron, respectively. Values of permeability may be found in Sec. 4.

81. The total exciting current may be found as follows: The wattless or magnetising component is

$$I_a = \frac{P_a}{E} \qquad \text{(amp.)} \qquad (26)$$

The energy component, assuming I^2R losses in the winding to be negligible, is

$$I_r = \frac{P_h + P_e}{E} \qquad \text{(amp.)} \qquad (27)$$

and the total exciting current is

$$I = \sqrt{I_r^2 + I_a^2} \qquad \text{(amp.)} \qquad (28)$$

The copper loss in the winding is

$$P_c = I^2R \qquad \text{(watts)} \qquad (29)$$

Adding this to the core loss, we have approximately for the total loss

$$P = P_h + P_e + P_c \text{ (watts)} \qquad \text{(watts)} \qquad (30)$$

Then the energy component of the exciting current is

$$I'_r = \frac{P}{E} \qquad \text{(amp.)} \qquad (31)$$

and the total exciting current is

$$I' = \sqrt{I'^2_r + I_a^2} \qquad \text{(amp.)} \qquad (32)$$

which is approximately correct. This current can be used to find a new copper loss, and the calculations can be repeated as far as it is thought worth while.

82. Effect of temperature on iron losses. The losses in the core decrease with a rise in temperature, and since the core losses form the major portion of the total losses, the efficiency will increase with a rise in temperature.

83. Lamination of magnetic circuit. The magnetic circuit should naturally be laminated; this may be done in a way similar to that used in transformer construction; or the core can be made solid, and slots $\frac{1}{16}$ in. wide and $\frac{1}{4}$ in. or more in depth milled lengthwise in it. The magnetic circuit can also be constructed by winding iron ribbon spirally about a spider.

84. Pulsation of pull. In single-phase magnets the pull varies from zero to a maximum, and back, twice during each cycle. This causes a vibration of the armature against the core and gives rise to a considerable **noise.** The latter may be largely overcome by means of a **shading coil,** linked with a portion of the flux in the end of a core or in an armature. This splits the phase so that flux is always present in the sealed air-gap, and the pull is never zero.

85. Air-gap pull. If there was no reluctance excepting in the air gap and also if there were no iron losses, the mean effective air-gap pull* would be constant regardless of the length of the air gap. In practical electromagnets, the presence of reluctance and iron losses prevents the current from falling to zero when the air gap closes, so that, for a very short air gap, the pull characteristics are somewhat similar to those for continuous-current electromagnets.

86. Calculation of pull. For a given number of effective ampere-turns, the laws stating the pull with alternating-current electromagnets are identical with those for continuous-current electromagnets (barring core losses); but, since in constant-e.m.f. electromagnets the current is reduced as the reluctance of the air-gap is reduced, during the travel of the armature or plunger, the characteristics of alternating-current electromagnets are different from those for direct-current electromagnets. However, the true pull may be determined, for any length of air-gap, by calculating the effective ampere-turns for all lengths of air-gap and then calculating the pulls with the ampere-turns so deduced, by the equations given in Par. **83.**

* Underhill, C. R. "Alternating-current Electromagnets;" *Electrical World*, 1914, Vol. LXIII, p. 260.

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POLYPHASE ELECTROMAGNETS

87. Test data on two-phase electromagnet. Fig. 33 shows the relation between volt-amperes and pounds pull for a two-phase magnet designed and tested by D. L. Lindquist.* The magnet contained four coils, each wound with 220 turns of No. 14 A.W.G. copper wire, the cross-sectional area of the core being 1.94 sq. in. The test was made with the magnet-winding connected to a two-phase 60-cycle system. The method of connecting the coils is shown in Fig. 34.

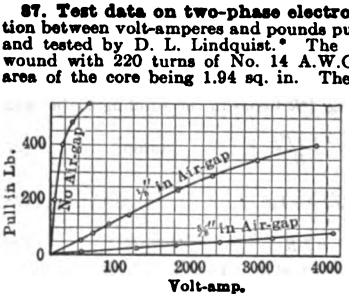


FIG. 33.—Relation between volt-amp. and pull for a two-phase electromagnet.

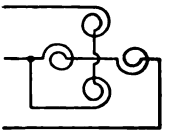


FIG. 34.—Connections of two-phase electromagnet.

88. Pulsation of pull. Theoretically, the pull in magnets equipped with polyphase windings should be constant and equal to the maximum pull due to the maximum flux produced in one phase. This, however, is only true when the e.m.f. wave is a pure sine-function. Distortion of the e.m.f. wave will alter the mean effective pull. In any case, if the load exceeds the minimum instantaneous pull, there will be chattering exactly similar to that in a single-phase magnet.

89. Polyphase magnets used in signal relays are, in effect, induction motors so designed that the rotor can revolve through a sufficient angle to operate the contacts. This gives a constant drag on the rotor due to the rotary magnetic field and avoids chattering.

HEATING OF ELECTROMAGNETS

90. Capacity limited by heating. The capacity of a given electromagnet is limited by the amount of heat which it can dissipate per unit time without exceeding a given or safe temperature rise.

91. The temperature rise can be measured by placing a thermometer against the outside surface or by measuring the change in resistance (Sec. 3). The general formula given below supposes the mean temperature rise to be measured by the thermometer method. The resistance method gives results which are from 1.5 to 2 times greater than those obtained with a thermometer, depending upon the depth of the winding, circulation of the air, etc.

92. Formula for temperature rise. The general equation for the final temperature rise in a given coil is

$$t_e = k\frac{P}{A} \qquad \text{(deg. cent.)} \qquad (33)$$

where P is the power, in watts, dissipated in the coil; A the outside cylindrical surface of the coil (the ends are counted only in short coils, and the inside surface is not counted), and k is the temperature rise in centigrade degrees per watt per square inch of outside cylindrical surface. Values for the constant, k, in the above formula differ widely according to the proportions of the coil, the depth of the winding, etc. The following values represent average practice. For open electromagnets, $k = 130$; for iron-clad electromagnets, $k = 95$.

93. Safe temperature limits. The final temperature rise varies between 50 deg. cent. and 75 deg. cent. according to the specifications, the climate, the depth of winding, etc. The internal temperature rise is limited to that which

* Lindquist, D. L. "Polyphase Magnets;" *Electrical World*, 1906, Vol. XLVIII, p. 128. "Characteristic Performance of Polyphase Magnets," *Electrical World*, 1906, Vol. XLVIII, p. 564.

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the insulation can successfully withstand. The temperature inside the coil must necessarily be higher than that on the outside.

94. The watts per square inch for a series of standard magnets are given in Par. **68.** These values may be used for magnets within the range of proportions shown in Fig. 17, Fig. 20, Fig. 27 and Fig. 30.

95. Hot resistance. The approximate final resistance of a coil which has been in circuit for a sufficient length of time to become thoroughly heated is

$$R_t = R_c(1 + \alpha_{t_c} t) \qquad \text{(ohms)} \qquad (34)$$

where R_c is the resistance of the coil at room temperature; R_t the final resistance; t, the rise in temperature in deg. cent. above room temperature; and α_{t_c} is the mass resistance temperature coefficient at room temperature (see Sec. 4). The standard room temperature is 25 deg. cent. Roughly, it may be assumed that the resistance of copper will be increased 1 per cent. for each 2.5 deg. cent. rise in temperature, or for each 5 deg. fahr.

96. Coils impregnated with high-melting and good heat-conducting compounds are able to withstand more applied power than untreated coils. In alternating-current magnets, the ferric parts also become heated (see Par. **78**).

MAGNET WIRES

97. Wire insulation. Wires commonly used in the winding of electromagnets are insulated with enamel, silk or cotton; or combinations of enamel and cotton, or enamel and silk.

98. Table of Diameters of Magnet Wires

(The Acme Wire Co.)

Size A. W. G.	Single-cotton covered	Enamel and cotton	Single-silk covered	Enamel and silk	Enamel
10	.1069	.1088	.....	.....	.1038
11	.0957	.0975	.....	.....	.0925
12	.0858	.0876	.....	.....	.0826
13	.0770	.0787	.....	.....	.0737
14	.0691	.0708	.....	.....	.0658
15	.0621	.0635	.....	.....	.0585
16	.0558	.0573	.....	.....	.0523
17	.0503	.0517	.....	.....	.0467
18	.0453	.0468	.....	.....	.0418
19	.0409	.0424	.....	.....	.0374
20	.0360	.0372	.0340	.0352	.0332
21	.0325	.0335	.0305	.0315	.0295
22	.0294	.0305	.0274	.0285	.0265
23	.0266	.0277	.0246	.0257	.0237
24	.0241	.0252	.0221	.0232	.0212
25	.0219	.0229	.0199	.0209	.0189
26	.0200	.0208	.0180	.0188	.0168
27	.0182	.0190	.0162	.0170	.0150
28	.0166	.0174	.0146	.0154	.0134
29	.0153	.0160	.0133	.0140	.0120
30	.0140	.0147	.0120	.0127	.0107
31	.0130	.0137	.0109	.0117	.0097
32	.0120	.0126	.0100	.0106	.0086
33	.0111	.0117	.0091	.0097	.0077
34	.0103	.0109	.0083	.0089	.0069
35	.0096	.0102	.0076	.0082	.0062
36	.0090	.0096	.0070	.0076	.0056
37	.....	.0090	.0065	.0070	.0050
38	.....	.0085	.0060	.0065	.0045

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99. Space factor. The most efficient winding is that which contains the maximum amount of conducting material; hence a thin insulation of high dielectric strength is desirable. The space factor or **activity coefficient** is the ratio of the space occupied by the insulated conductor to that occupied by the bare conductor. This is conveniently expressed in terms of turns per square inch. The Tables (Par. **98, 102, 104, 106**) show the relative values for the various wires. Enamel and silk, and enamel and cotton, are designed to replace double-silk- and double-cotton-covered wires, respectively; the former two have higher activity coefficients and greater dielectric strengths than the latter two.

WINDING CALCULATIONS

100. Winding formulas. In what follows let

d = diameter of bare copper wire in inch,
R_l = ohms per linear inch,
d_l = diameter of insulated wire in inch,
t'' = turns per linear inch,
n'' = layers per inch,
N_a = turns per square inch,
R_v = ohms per cubic inch.

Then the number of **ohms per linear inch** is

$$R_l = 8{,}628 d^{-2} 10^{-10} \tag{35}$$

and

$$t'' = d_l^{-1} \text{ (or is found by actual count)} \tag{36}$$

For layer windings with no paper between layers,

$$n'' = t'' \text{ (approx.)} \tag{37}$$

When paper is used,

$$n'' = (d_l + t_p)^{-1} \tag{38}$$

wherein t_p is the thickness of the paper layer.

The **turns per square inch** and the **ohms per cubic inch** are given by

$$N_a = t''n'' \tag{39}$$

$$R_v = N_a R_l \tag{40}$$

The properties and dimensions of bare copper wires will be found in Sec. 4. Furthermore let

T = thickness of wall of winding in inches,
L = actual length of winding in inches,
p_a = average perimeter or mean length of turn in inches,
S = longitudinal cross-sectional area of winding in square inches,
V = volume of winding in cubic inches.

The **winding cross-section** and the **winding volume** are

$$S = TL \tag{41}$$

$$V = Sp_a \tag{42}$$

In all usual shapes of coils, the **thickness of coil-wall** is $T = n/n''$, where n is the number of layers. For coils wound on cores or forms of the shapes in Fig. 35, the equation

$$p_a = 2(a + b + 1.571T - 0.859r) \tag{43}$$

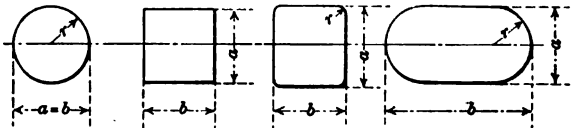


FIG. 35.—Core shapes and dimensions for electromagnet windings.

is general and gives the **mean length of turn** for coils with cores of any of these shapes. In the case of the perfectly square or rectangular core, the radius, r, is zero; whereas, in the case of the round core, it is, of course, equal to one-half of the diameter.

For a round core only,

$$p_a = \pi(D_l + T) \tag{44}$$

where D_l is the inside diameter of the coil. In all cases, the dimensions of

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the insulated cores are assumed, so far as the inside dimensions of the winding are concerned.

The **total number of turns** in a winding is given by

$$N = TLN_s \text{ or } N = n''t''TL \tag{45}$$

The **resistance** of a winding is expressed by

$$R = VR_t \text{ or } R = p_c NR_l \tag{46}$$

101. Formula for ampere-turns. The calculations of windings for electromagnets are generally controlled by the ampere-turns to be developed and the energy loss in watts which can be safely allowed. This reduces to the problem of finding the size and kind of insulated wire which will give the proper proportions of turns and resistance. For continuous-current electromagnets, the equation for the ampere-turns for a given e.m.f. is

$$NI = \frac{E}{p_c R_l} \tag{47}$$

Conversely, the size of wire is found from the table opposite the nearest value for $R_l = E/NIp_c$. For the proper dimensions of a coil to radiate a given amount of heat see Par. 92.

102. Table of Turns per Square Inch; Solid Layer Winding

(The Acme Wire Co.)

Size A.W.G.	Single-cotton covered	Enamel and cotton	Single-silk covered	Enamel and silk	Enamel
10	87.5	84.5	.....	.....	92.5
11	109	105	.....	.....	117
12	136	130	.....	.....	147
13	169	161	.....	.....	184
14	210	199	.....	.....	231
15	260	248	.....	.....	292
16	321	304	.....	.....	366
17	396	374	.....	.....	458
18	488	456	.....	.....	572
19	598	556	.....	.....	715
20	772	722	865	807	907
21	947	890	1,075	1,010	1,150
22	1,155	1,075	1,330	1,230	1,425
23	1,410	1,303	1,650	1,510	1,780
24	1,720	1,575	2,045	1,860	2,220
25	2,080	1,910	2,520	2,290	2,800
26	2,500	2,310	3,090	2,830	3,540
27	3,020	2,770	3,810	3,460	4,440
28	3,630	3,300	4,690	4,220	5,570
29	4,270	3,910	5,650	5,100	6,950
30	5,100	4,630	6,950	6,200	8,730
31	5,920	5,330	8,410	7,300	10,650
32	6,950	6,300	10,000	8,900	13,500
33	8,120	7,300	12,080	10,650	16,900
34	9,430	8,410	14,500	12,600	21,000
35	10,850	9,610	17,300	14,900	26,000
36	12,350	10,850	20,400	17,300	31,900
37	.....	.....	23,700	20,400	40,000
38	.....	.....	27,800	23,700	49,300

103. Final calculations. Having found the proper size of wire, it is customary to make preliminary calculations for turns, resistance, etc., and

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then to make the final calculations after the turns per layer and number of layers have been determined from the preliminary data.

For a round winding, with given core, length, size of wire and resistance, the **outside diameter** will be

$$D = \left[\frac{4}{\pi L}\left(\frac{R}{R_s}\right) + D_1^2\right]^{\frac{1}{2}} \qquad (48)$$

The approximate **thickness of wall** of winding will be

$$T = \frac{D - D_1}{2} \qquad (49)$$

The **number of layers** will be $n = Tn''$, and a new value for T will be found for an exact number of layers, by $T = n/n''$. The **mean length of turn** will be $p_a = \pi(D_1 + T)$ and the **outside diameter** will now be $D = D_1 + 2T$. The **number of turns** will be $N = n''L$, and the **resistance**, $R = Np_aR_l$. For round windings, the **radiating surface** is $A = \pi DL$, where A is the cylindrical surface.

104. Ohms per Cubic Inch; Solid Layer Winding

(The Acme Wire Co.)

Size A.W.G.	Single-cotton covered	Enamel and cotton	Single-silk covered	Enamel and silk	Enamel
10	.00727	.00702	.....	.....	.00768
11	.0114	.0110	.....	.....	.0123
12	.0180	.0172	.....	.....	.0194
13	.0282	.0268	.....	.....	.0307
14	.0442	.0418	.....	.....	.0485
15	.0690	.0658	.....	.....	.0774
16	.1072	.1017	.....	.....	.1225
17	.167	.158	.....	.....	.193
18	.260	.243	.....	.....	.305
19	.401	.373	.....	.....	.479
20	.652	.610	.731	.682	.767
21	1.01	.948	1.145	1.075	1.225
22	1.55	1.45	1.788	1.652	1.915
23	2.39	2.21	2.79	2.56	3.01
24	3.67	3.36	4.37	3.97	4.74
25	5.60	5.14	6.79	6.17	7.54
26	8.50	7.85	10.5	9.62	12.03
27	12.93	11.85	16.3	14.8	19.0
28	19.6	17.8	25.3	22.8	30.1
29	29.1	26.6	38.5	34.8	47.3
30	43.8	39.7	59.6	53.2	74.8
31	64.1	57.7	91.1	79.1	115.3
32	94.9	86.0	136.5	121.5	184.2
33	140	125.8	208	183.5	291
34	205	183	315	274	456
35	297	263	473	408	711
36	426	375	705	597	1100
37	.....	.....	1032	888	1742
38	.....	.....	1525	1300	2710

CONSTRUCTION OF COILS

105. Methods of winding. There are two standard methods of winding coils. The original method is to prepare the bobbin for the wire and then to wind the coil by rotating the bobbin in a small special lathe and guiding the wire by hand. In the other method the wire is wound in a form, and then taped or otherwise mounted.

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106. Table of Ohms per Pound
(The Acme Wire Co.)

Size A.W.G.	Single-cotton covered	Enamel and cotton	Single-silk covered	Enamel and silk	Enamel
10	.0314	.0312	.....	.....	.0315
11	.0498	.0496	.....	.....	.0502
12	.0789	.0784	.....	.....	.0797
13	.1255	.125	.....	.....	.1278
14	.199	.198	.....	.....	.2015
15	.315	.312	.....	.....	.3200
16	.500	.496	.....	.....	.509
17	.792	.787	.....	.....	.809
18	1.26	1.25	.....	.....	1.285
19	1.99	1.98	.....	.....	2.042
20	3.04	3.02	3.23	3.19	3.24
21	4.98	4.95	5.15	5.08	5.16
22	7.90	7.82	8.13	8.05	8.19
23	12.5	12.38	12.95	12.8	13.02
24	19.8	19.5	20.6	20.3	29.7
25	31.3	30.8	32.5	32.1	32.9
26	49.4	48.7	51.5	50.9	52.2
27	77.7	76.3	81.4	80.5	82.9
28	121.8	119.5	129	127	131.5
29	192	188.5	204	201	208.5
30	300	296	323	319	334
31	472	464	509	503	530
32	741	718	805	793	840
33	1,135	1,115	1,267	1,248	1,333
34	1,758	1,710	1,990	1,950	2,115
35	2,750	.....	3,130	3,010	3,350
36	4,270	.....	4,940	4,740	5,320
37	.....	.....	7,630	7,370	8,440
38	.....	.....	11,920	11,580	13,400

107. Insulation. The use of electromagnets on lighting and power circuits makes it necessary to provide additional insulation between adjacent layers of wire to prevent a breakdown at the points of maximum e.m.f. between layers, when the circuit is suddenly broken. It is customary, therefore, to place one or more wraps of thin paper between adjacent layers which, as a further advantage, makes it possible to wind coils of fine wire evenly in layers. Enameled wire is particularly adapted for this form of coil since the e.m.f. between adjacent turns in a layer is very low; consequently more turns per layer may be obtained and a high activity for the coil maintained.

108. Form winding. Coils with or without paper between successive layers may be wound directly into the bobbin, or into forms, and the coils mounted later. It is customary in such cases to guide the wire by means of a traverse screw or a cam. In one well-known method, several coils are simultaneously wound by automatic machinery. Coils wound in a so-called haphazard manner are well named, since the e.m.f. between adjacent wires may be sufficient to puncture the insulation under sudden fluctuation of the current.

109. Drying and treating. In general, coils should be thoroughly dried out, dipped in insulating varnish and baked, or else treated with some melting compound. This protects them from moisture and assists in conducting away the internal heat. Also see Par. **96.** Coils wound with tape as a finish should be treated in the same manner as the field coils of electric machines.

110. Mounting. A good method of mounting direct-current windings after impregnation is to wrap a thin brass tube with oiled muslin, fringed

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at the ends so that the fringes will overlap one another when bent at right angles to the tube. The coil is then mounted on the muslin-covered tube and several oiled muslin washers are placed on each end. A slotted fiber washer is mounted at the end with the inside lead, and the lead is brought out through the slot after being wound once around the tube; the inside diameter of this washer should be sufficient to slip over the turn of the lead. More oiled-muslin washers are then put on, and the fringes are fanned out at both ends of the coil, after which heavy fibre end washers are put on and the ends of the brass tube spun over. This makes a very solidly constructed and well-insulated coil. In alternating-current coils, the brass tube must be slotted lengthwise. When flat ribbon leads are used, it is not necessary to use a slotted washer.

All splices should be soldered or brazed and thoroughly protected with oiled muslin. The leads should be tied in position with stout twine.

111. Covering. Mounted coils are covered with cord, pressboard, oiled muslin, etc., and are often dipped in black air-drying varnish to give them a protecting finish.

TESTING OF MAGNETS

112. Measurement of pull. The attracting effort of a small portative magnet or a small tractive magnet, with the armature or plunger in contact with the pole faces or stop, may be measured with a spring balance. Large magnets may be tested by direct loading or by loading through a system of levers. The **pullout point** is not preceded by any warning and, in order to obtain accurate load readings, the load must be applied at a uniform rate and under perfect control.

A simple method is to hang a bucket below the weights and to pour water or shot into it until an amount equal to a weight unit is exceeded, when the bucket may be removed and the equivalent weight placed in position; then the empty bucket is again hung in place and filled, this cycle of operations being continued until the pullout point is reached, when the total weight is determined.

113. The pull tests, for various lengths of air-gaps, may be made by the use of brass discs or rings of thicknesses arranged in decades. Thus the first group may be 1 in., 2 in., 3 in., and 4 in. respectively, with which any combination in thickness from 1 in. to 10 in. may be obtained. This idea may be carried out as far as desired. Twelve spacers will give 1,000 combinations. The measurement of the pull should be made as outlined in Par. 112.

114. The heating test requires an ammeter, a thermometer (or voltmeter), a watch and a rheostat. Fig. 36 shows the connections for a test where the temperature rise is determined by the change in resistance (Sec. 3). Instruments and general measurements are treated in Sec. 3. The temperature rise can be measured either by the resistance method or with a thermometer placed against the outside of the winding. In making the test the current should be kept at a constant value I by means of the rheostat, and the thermometer (or, in Fig. 36, the voltmeter) read at regular time intervals. While making the test, either the temperature or the e.m.f. drop should be plotted with time; this will give the heating curve and show when the final temperature has been reached.

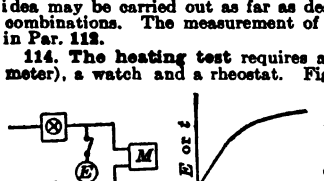


FIG. 36.—Connections for heat run, determining temperature rise by resistance method.

115. The resistance test is usually made with a Wheatstone bridge or a modification* of the same designed to test the coils very rapidly.

116. Test for short-circuited turns. Coils designed for use on alternating-current circuits are tested for short-circuited turns by placing them on the core of a special transformer, whereby a high e.m.f. is induced in them.

117. The breakdown test for direct-current coils is accomplished by placing them on a laminated core before mounting; then heavily overloading

* Underhill, C. R. "The Design of a Quick-acting Wheatstone Bridge," *Electrical World*, 1910, Vol. LVI, p. 29.

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them, and suddenly interrupting the circuit so as to induce a high momentary e.m.f. A reduction in the resistance of the coil is, as determined by subsequent measurement, an indication of punctured insulation in the winding. Coils mounted on brass tubes covered with six wraps of oiled muslin withstand a regular commercial test, from coil to tube, of 3,500 volts alternating effective value.

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INDUCTION COILS

BY CHARLES R. UNDERHILL

GENERAL

119. Induction coils may be divided into two classes: those with a primary winding only, and those with both primary and secondary wind-

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ings. The former are used extensively in connection with the ignition of internal-combustion motors. The function of both types is to respond to very sudden fluctuations of the e.m.f. in the primary circuit. For this reason, they have open magnetic circuits, which partly accounts for their generally low efficiency.

In telephony, the function of the induction coil is to accurately transform the complex waves of e.m.f. and current corresponding to the sound waves produced by articulate speech. It is, therefore, in this particular case, simply a transformer with an open magnetic circuit. Induction coils of the secondary type are also used in radio telegraphy, internal-combustion motor ignition, etc.; they operate on the principle of the gradual or progressive storage of energy, which is then suddenly discharged, and the cycle repeated.

The performance of the primary type of induction coil has an important bearing on the behavior of secondary-type coils of the jump-spark type and, for this reason, the primary-type coil is treated first and separately.

PRIMARY-TYPE INDUCTION COILS

120. Definition. A primary-type coil is a reactor (Sec. 6) designed to receive electrical energy, then convert it into magnetic energy, storing as much of the latter as feasible, and finally to reconvert it suddenly into electrical energy. The ultimate object is to utilise the heat of the resulting spark, when the circuit is suddenly broken. The rupture of the circuit usually takes place in the cylinder of an internal-combustion engine or motor.

121. Theory. As commonly made, the primary-type induction coil consists of relatively few layers of coarse magnet wire wound over a core consisting of a bundle of soft-iron wires. When the circuit is closed through a battery, current flows through the coil and magnetizes the core; the counter-e.m.f. generated by the magnetic flux cutting the turns of wire in the coil opposes the e.m.f. of the battery, so that a definite time interval is required to fully charge the iron core with magnetic energy.

The break is designed to have a snap-action which causes the circuit to be opened very rapidly, as soon as the flux in the core attains its most efficient value; thereupon the current and the flux decrease at a very rapid rate, and at the same rate, to zero. This sudden rate of change in the flux induces a high e.m.f. in the coil, proportional to $\partial\phi/\partial t$, in the same direction as the battery e.m.f., tending to retard the decrease of the current, and thus prevent the sudden collapse of the magnetic field. Hence, at the point of rupture, or break, there results a bright spark or arc, usually varying from $\frac{1}{4}$ in. to $\frac{1}{16}$ in. in length, the energy of which is the equivalent (barring losses) of the magnetic energy previously stored in the core. The value of the current at the instant that the metallic circuit is broken is given in Par. 30, Eq. 6, under "Magnets."

122. Stored magnetic energy. The magnetic energy, in joules, stored in time t is

$$W = \frac{L}{2} i^2 \qquad \text{(joules)} \qquad (50)$$

where L is the inductance in henrys and i is the value of the current in amperes at the end of time t in seconds. This is the **energy of the spark** (less losses).

123. The inductance of the coil is expressed by

$$L = 80N^2d10^{-9} \qquad \text{(henrys)} \qquad (51)$$

approximately, for cores having ratios of length to diameter between 10 and 15, where N is the number of turns in the coil, and d is the diameter of the core in centimeters.* The time, t, required for the current to attain 63 per cent. of its final value is the **time constant** (Sec. 2) of the circuit; it is numerically equal to L/R. By assuming that the rate of current increase is nearly uniform between 0 and L/R seconds, which is approximately correct, the value of the current strength may be estimated for any corresponding time after closing the circuit.

* Armagnat, H. "Induction Coils" (Translated from the French by O. A. Kenyon); New York, McGraw-Hill Book Co., 1908.

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124. Test characteristics. In Fig. 37 are shown the test characteristics* of a coil with circuit constants of $R = 9$ ohms, and $L = 0.02$ henry. When the circuit was closed for 0.02 second, with an e.m.f. of 8 volts, the **stored energy** (or spark energy) was 0.025 watt-second. The curve for 12 volts is also shown. It will be seen that the current at any instant is directly proportional to the e.m.f.

The time required for the current to rise from 0 to 63 per cent. of its ultimate value may be lessened by reducing the inductance or increasing the resistance. In general, a gain in time causes a corresponding loss in energy stored. The voltage should be sufficient to overcome variations of the resistance of the contacts, but not great enough to hold the arc too long after the contacts are separated. In practice, battery e.m.fs. of from 6 to 12 volts are employed, but a good rule is to keep the e.m.f. as low as possible. When a generator is used instead of a battery, the resistance and the inductance of the generator must be added to the constants of the rest of the circuit.

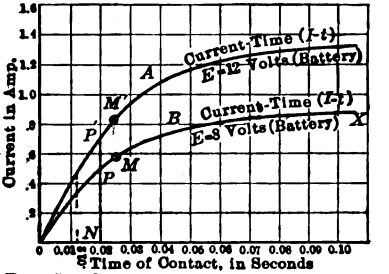


FIG. 37.—Current-time curves of a primary-type induction coil.

125. Instantaneous current. Fig. 38 shows an **oscillagram** from a test† of a primary-type coil. The constants of the circuit were $E = 4$ volts $R = 1$ ohm, $L = 0.01$ henry, and the final value of the current, I, 4 amp. The circuit was closed at A and the current attained a value of 63 per cent. of 4 amp. at B, in 0.01 sec. The electric circuit was suddenly broken at B and current had ceased to flow, *i.e.*, there was no arc, after the circuit had been broken, for 0.0015 sec. The circuit remained broken from C to A, and then the cycle was repeated. If the circuit had been left closed for more than 0.01 sec., the value of the current, for varying time, would have been represented by the dotted logarithmic curve.

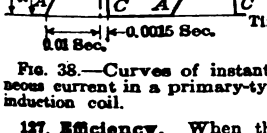


FIG. 38.—Curves of instantaneous current in a primary-type induction coil.

126. Variation of inductance and resistance. It will be seen that the amount of energy, W, stored magnetically, for a given primary coil, is proportional to the time that the circuit is closed. Owing to the fact that the inductance is not constant, it is difficult to estimate accurately the time-constant of the circuit. A certain amount of resistance is also introduced at the contacts, due to corrosion, etc. For these reasons, the predetermination of the characteristics of such a coil is only approximate.

127. Efficiency. When the coil circuit is broken, several variables must be considered. It is exceedingly difficult to calculate the speed of the break exactly. The resistance of the arc at the break depends upon the temperature and the pressure of the medium in which the arc occurs, the strength of the current, the self-induction of the circuit and the material of the electrodes. All of these factors enter into the determination of the time required to reduce the current to zero. Prof. Bailey estimated the average e.m.f. developed at the break, in the coil tested (Par. 125), to be 30 volts, and the efficiency to be 56 per cent.; however, he considered that the efficiency might be increased to 85 per cent. by increasing the inductance four times and permitting the current to rise to 1.25 amp.

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* Springer, F. W. "The Design and Operation of Spark Coils;" *Electrical World*, 1907, Vol. L, p. 1163.

† Bailey, B. F. "The Induction Coil;" *Electrical World*, 1910, Vol. LV, p. 943.

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SECONDARY-TYPE INDUCTION COILS

128. Theory. Fig. 39 shows the circuit diagram of a typical secondary-type induction coil. The circuit is closed at *S* and current established in

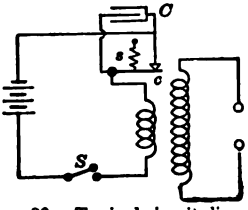


FIG. 39.—Typical circuit diagram for secondary-type induction coil.

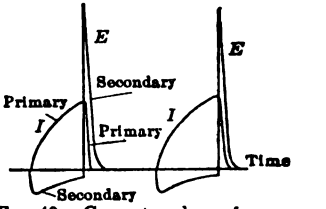


FIG. 40.—Current and e.m.f. curves of a secondary-type induction coil without condenser.

the primary circuit; this current produces a flux in the core and when the flux reaches a certain value the pull exerted on the interrupter contact arm

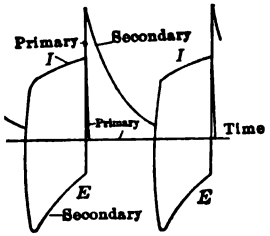


FIG. 41.—Effect of loading the secondary. (No condenser.)

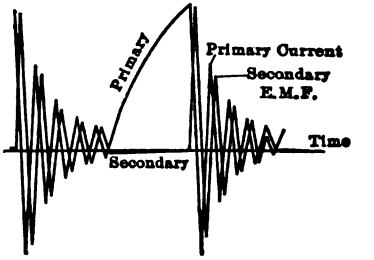


FIG. 42.—Curves of current and e.m.f. in an unloaded secondary-type coil with condenser.

is sufficient to overcome the pull of the spring, *s*, and opens the circuit at *C*. The circuit being open, the flux quickly decreases to zero and thus generates a high value of e.m.f. in the secondary winding, which consists of many turns.

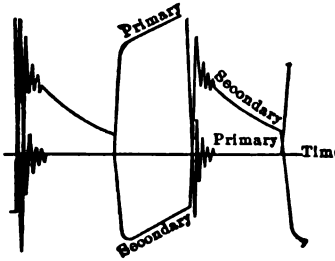


FIG. 43.—Current curves of a loaded secondary-type coil with condenser.

When no condenser (Par. **169**) is used and the secondary circuit is open, no current flows through the secondary and, consequently, the effect of the secondary upon the primary is nil, excepting for the negligible charging current in large coils. All actions in the primary take place exactly as though the secondary were not present. Fig. 40* is the same as Fig. 38 with the secondary e.m.f. curves added. The effect of **loading the secondary** (without condenser) is shown in Fig. 41.

129. Effect of condenser. Fig. 42 shows the effect of the condenser

* Bailey, B. F. "The Induction Coil;" *Electrical World*, 1910, Vol. LV, p. 943.

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(Fig. 39) with an unloaded secondary, while Fig. 43 represents the effects of loading the secondary. These curves (Figs. 41, 42 and 43) are taken from oscillograms made by Prof. Bailey. The condenser, with the local inductance of the primary, constitutes an oscillating circuit. The self-induction in the primary is small; hence the rate of oscillation is high. The oscillations in the primary react upon the secondary, producing an oscillation superimposed upon the logarithmic current-time curve.

130. Operation of interrupter. The interrupter should be so designed that the current may increase to its proper value and the circuit then suddenly open automatically, in order that the time rate of change in the flux may be as great as possible. The interrupter is usually made adjustable for this purpose. When it cannot be relied upon to give a sufficiently brief duration of contact, it is safer to increase the resistance of the primary and thus decrease the time-constant, rather than to increase the e.m.f. of the battery. The condenser (Par. 169) should have just sufficient capacity to prevent sparking.

131. The design of induction coils is largely empirical, there being many points upon which there are no definite data. Prof. Bailey and others have published some excellent papers on the theory of induction coils, from which part of the foregoing data have been taken (see "Bibliography").

132. Core design. Fig. 44 shows a curve plotted* between flux in lines per square inch per ampere-turn per inch length of coil ($\mathfrak{G}/NI$), and the ratio of core length to net cross-sectional area of core (l_c/A_n). It must be noted that the net area is used; this is given by

$$A_n = a\frac{\pi d^2}{4} = 0.7\frac{\pi d^2}{4} \quad \text{(sq. in.)} \qquad (52)$$

where d is the core diameter in inches, and a is the space factor (Par. 134). This curve was plotted from data taken from tests made on cores of commercial annealed round iron wire 0.062 in. in diameter. In every case, the exciting coil was 3 in. long, and consisted of 191 turns of No. 16 A.W.G. copper wire wound in 4 layers. The flux was measured with an exploring coil of 20 turns placed in the centre and outside of the exciting coil. The points plotted on the curve (Fig. 44) are for a set of cores 1 in. in diameter and of different lengths; the circles plotted on the curve are for a set of cores 4 in. long and of various diameters.

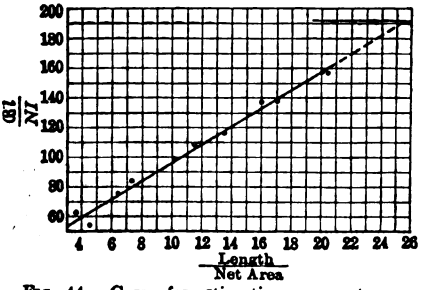


FIG. 44.—Curve for estimating ampere-turns.

It is well to note that the same ratio of length to diameter can correspond to any ratio of length to net area, and that the flux density produced per ampere-turn per inch length of coil varies with the latter ratio.

133. Flux density. Based upon the tests plotted in Fig. 44, the flux density along the middle section of the core of a straight-core coil is, according to Mr. O. A. Kenyon,

$$\mathfrak{G}_{max} = \frac{\sqrt{2}\,NI}{l}\left(6.1\frac{l_c}{A_n} + 35\right) \qquad \text{(maxwell's per sq. in.)} \qquad (53)$$

where N is the number of turns, I the maximum current in amperes, l the length of the coil, l_c the length of the core, and A_n the net cross-sectional area of the core. All dimensions are in inches.

* Kenyon, O. A. from data by Springer, F. W. "The Design and Operation of Spark Coils;" *Electrical World*, 1907, Vol. L, p. 1163.

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134. The space factor of the core is that per cent. of the total area which is occupied by iron. In the cores tested by Mr. Springer, the space factor varied from 0.675 to 0.70 and averaged 0.687.

135. Table of Core Dimensions from Practice
(Ehnert) *

Spark length (cm.)	Core length (cm.)	Core-wire diameter (mm.)	Space-factor
8	15–20	0.8	0.84
10	20–25	1.0	0.82
15	25–35	1.2	0.80
20	30–42	1.4	0.78
25	35–50	1.5	0.77
30	48–60	1.6	0.76
35	52–58	1.7	0.75
40	62–70	1.8	0.74
50	80–90	1.9	0.73
60	100–120	2.2	0.715
70	120–140	2.5	0.70

136. The size of the primary wire should be so chosen as to produce heat at a very low rate, since there is almost no ventilation of the primary coil. The **current density** in the primary coil can vary between 600 and 1,200 amp. per square inch. It must be remembered also that in coils with large cores the **hysteresis** loss is important. See Par. **79**.

137. Table of Sizes of Primary Wire from Practice
(Ehnert) *

Spark length, cm.....	8	10	15	25	35	50
Wire diameter, mm.....	1	1.2	1.5	2.0	2.5	3
Nearest size A. W. G.....	18	17	15	12	10	9

SECONDARY WINDINGS

138. The necessary number of secondary turns to give a certain secondary e.m.f. depends upon the value of the flux in the core, the type of interrupter, the constants of the circuit, etc. As yet there is no law of general application which will permit the accurate or even approximate determination of the number of secondary turns. When the magnetic circuit and the primary winding are finished, an experiment can be made which will determine the approximate number of secondary turns. Using an interrupter that will give a definite and invariable duration of contact, find the value of e.m.f. generated per turn, in a coil of only a few turns, and then divide the total desired e.m.f. by this value to obtain the required number of secondary turns.

139. Table of Dimensions of Secondary Winding from Practice
(Ehnert) *

Spark length, cm.....	5 to 10	12	15	25	35	50
t, cm. (Fig. 46).....	0.4	0.5	0.6	0.7	0.8	0.9
h, cm. (Fig. 46).....	1.5	2.0	2.5	3 to 3.5	4.5	6 to 7

* Ehnert, E. W. "Theorie und Vorausberechnung der Funkeninduktoren;" *Electrotechnik und Maschinenbau*, 1907, Vol. XXV, pp. 337, 361 and 377.

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140. Limiting the secondary e.m.f. If too many secondary turns are used, the maximum value of e.m.f. can be limited by connecting the terminals to a **spark-gap**, the length of which corresponds to the maximum permissible e.m.f.

141. The size of secondary wire does not vary greatly. For coils giving long sparks, Ehnert states that in practice the wire varies in sizes from those equivalent to No. 35 to No. 38 A.W.G.; and for those coils giving short hot sparks, it varies from No. 30 to No. 34 A.W.G.

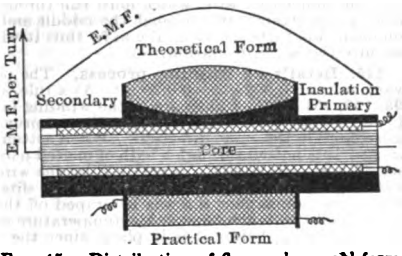


FIG. 45.—Distribution of flux and general form of coil.

142. Arrangement of windings; layer method. There are two general methods of arranging the windings, namely, the **layer method** and the section or **"pie" method** (Par. 144). Fig. 45 shows the layer method; the upper half shows the theoretical form of the major insulation and the secondary coil, while the lower half shows the practical form. The curve at the top shows the e.m.f. generated per turn in the secondary coil at different positions along the core. This curve shows that turns near the end of the core are very much less effective than near the middle. Designers differ as to the proper length of the secondary coil, but as a rule it varies from 0.25 to 0.50 of the length of the core.

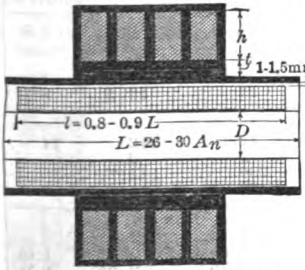


FIG. 46.—Coil proportions.

143. Construction of secondary-type coils for ignition. Immense quantities of induction coils are used in internal-combustion motor ignition. These coils usually have secondaries consisting of two sections mounted on a tube over the primary. The coils are wound evenly in layers, by automatic machinery, and several sheets of thin paper are inserted between successive layers during the winding process. These coils are subsequently treated with paraffin or some compound.

144. Arrangement of windings; "pie" method. Figs. 47 and 48 show the "pie" method. Coils giving a spark longer than 5 cm. (2 in.) generally require the secondary winding to be made in several sections. In Fig. 47, the inside of one "pie" is connected to the outside of the adjacent "pie," etc., while in Fig. 48, the adjacent coils are connected alternately at the inside and outside. Below the cross-sections are shown the e.m.f. diagrams. In the first, the maximum e.m.f. which can exist between two adjacent coils or "pies" is equal to the e.m.f. generated in one coil and is the same in all parts of the

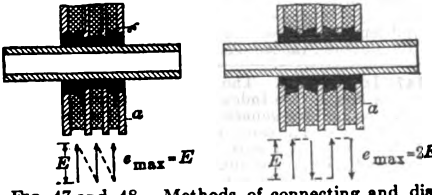


FIG. 47 and 48.—Methods of connecting and distribution of e.m.f. in pancake coils.

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coil; in the second, the difference in potential between two adjacent coils is zero at the points where they are connected (alternately inside and outside), and increases from that point to a maximum value equal to twice the e.m.f. generated in one coil.

At first sight it appears that the first system would require only half the insulation between sections or "pies" that the second would, but in practice the connecting wire, which must run through the insulation between the coils, is run straight out through the middle and requires sufficient insulation on each side to resist the coil e.m.f.; thus it will be seen that both systems require the same insulation.

145. Details of winding process. The pies are wound in thicknesses varying from 0.0625 in. to 0.25 in. As a rule, silk-covered wire is used (Par. **98, 102, 104, 106**). The core of the winding form is given a bevel, in order to tell the polarity of the coil at a glance, provided, of course, that all coils are wound in the same direction. When cotton-covered or silk-covered wire is used, it is passed through a bath of melted paraffin wax or compound while winding; the amount of wax retained by the wire is controlled by passing the wire from the bath through several paper slits, varied to suit the requirements; in this manner the wax is scraped off the wire to any desired extent. Care should be taken to have the temperature of the wax sufficiently high to prevent cooling before it is in place, since the wax serves to hold the wires together. Before winding, the wire should be thoroughly dried out in an oven.

146. Table of Dimensions of Induction Coils

Authority	Eddy*	Eddy*	*Elec. World*†
Spark, inches	12	6	1.5
Core:			
size wire A.W.G.	22	22	
diameter, inches	2.125	1(?)	1
length, inches	24	12.5	8
Primary:			
size wire A.W.G.	12	12	14
layers	2.5	2	
turns per layer	230	115(?)	
length coil, inches	22	11(?)	6
Ebonite tube:			
length, inches	26	14.5	
dia. outside, inches	3.5	2.75	1.69
dia. inside, inches	2.75	2.25	1.38
Secondary:			
size wire A.W.G.	34	34	‡
No. of pies	64	34	4
total turns	75,256	38,000	
Total length, inches	8	4.25	
dia. outside, inches	6	4.87	3.5

147. Insulation. The properties of insulators and other materials are given in Sec. 4 (see index). The **major insulation** between the primary and the secondary generally consists of a tube of such material as ebonite, hard rubber or micanite; or, in small coils, paraffined paper. Tubes made of "Micarta" also may be used. The **minor insulation** is generally obtained by impregnating the coils with paraffin wax or some compound. Over each layer of the primary winding is wound a thickness of oiled paper,

* Eddy, W. O. "The Design of a 12-in. Induction Coil;" *Electrical World*, 1907, Vol. XLIX, p. 40.

†"Questions and Answers;" *Electrical World*, 1906, Vol. XLVIII, p. 1064.

‡ The size or number of turns of secondary wire is not given. It is stated that 2 lb. of wire are required.

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and between the sections or "pies" of large secondaries there are discs built up of some treated material. The core wires should also be insulated by dipping them in some kind of insulating varnish.

INTERRUPTERS

148. Types of interrupters. Interrupters for induction coils may be divided into two distinct classes, namely; **mechanical** and **electrolytic**. The simpler form of mechanical interrupter (Fig. 49) is suitable for so-called medical coils. It is also used on small spark coils. This type of interrupter is not easily adjusted to different speeds, since it has a natural frequency of its own, and possesses considerable inertia.

149. An atonic interrupter is one that can be adjusted to operate at any frequency within very wide limits. A successful interrupter of this type is shown in Fig. 50. Modifications of this type are used on nearly all ignition coils, as well as on large and powerful induction coils. The hammer is attracted by the core and hits the spring contact, making a very sudden break. The duration of contact is regulated with the spring, s, and the duration of the break is controlled with the screws, r and r'. The spring, s, is so attached that it produces a pull which is practically uniform throughout the range of action and thus permits the magnetic force to accelerate the hammer very rapidly. The space between the hammer and the contact spring permits the hammer to attain an appreciable velocity and strike the spring a blow that breaks the circuit very suddenly. The contact spring is light and short, and has a very high natural frequency, thus making the "lost time" very small. This interrupter can be adjusted to operate on alternating-current supply, breaking the circuit when the maximum value of current is reached.

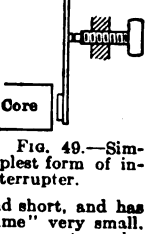


FIG. 49.—Simplest form of interrupter.

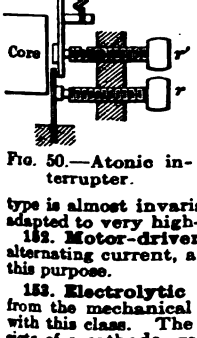


FIG. 50.—Atonic interrupter.

150. Oil-immersed interrupter. When the e.m.f. of the source exceeds 20 or 30 volts, the contacts are usually broken in an insulating liquid, which will extinguish the arc.

151. Mercury interrupters. For high-speed work, mercury interrupters are extensively used. There are two distinct kinds, namely; the **reciprocating type** and the turbine type. In the former, a reciprocating contact-point is plunged into and withdrawn from a basin of mercury, thus making and breaking the circuit. The plunging contact may be operated in a variety of ways, most usually with a small electric motor. The maximum speed of this type is limited by the tendency of the mercury to follow the plunging contact when it leaves the surface.

In the **turbine type**, a stream of mercury is made to play on a number of saw-like teeth, by revolving either the nozzle or the teeth. When the stream passes between the teeth the circuit is interrupted, and while in contact with the teeth it is closed. This type is almost invariably driven by an electric motor and is excellently adapted to very high-speed work.

152. Motor-driven interrupters can be adjusted to operate with alternating current, and are conveniently driven by synchronous motors for this purpose.

153. Electrolytic interrupters differ greatly in their characteristics from the mechanical interrupters described above. No condenser is used with this class. The best-known type is that due to **Wehnelt**, which consists of a cathode, generally a lead plate, immersed in a dilute solution of sulphuric acid together with the anode, which is a small platinum wire projecting into the electrolyte from a porcelain tube. The interrupter is adjusted by moving the anode up and down so as to change the amount of surface in action.

When a certain current density at the anode has been reached, the gas released at the surface of the anode increases the resistance at that point

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to such an extent that the circuit becomes practically interrupted. As soon as the current density falls the resistance decreases and the current again rises to its original value. Experiments show that electrolytic interrupters will operate in synchronism when connected in series or in parallel.

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CONDENSERS

BY CHARLES R. UNDERHILL

TYPES

155. Types and properties of condensers. There are three principal types of condensers. The most familiar one is the ordinary **plate condenser** used with induction coils, telephone and telegraph apparatus, where a very large capacity is not required. The plate type is also used for laboratory standards (Sec. 3) in measurements of various kinds. Where a very large capacity is required, the **synchronous condenser** (synchronous motor or synchronous converter with overexcited fields) is employed; such apparatus is outside the scope of this Section and will be found under Sec. 7. The third type is the **electrolytic condenser** which is treated later under its own head (Par. 175).

The properties of a condenser are covered fully in Sec. 2, but in brief, the chief function of a condenser is to store electrical energy for subsequent usage. Such storage of energy may take place in a variety of ways, according to circumstances: thus it may be constant, if the condenser is connected to a source of continuous e.m.f., or it may be intermittent, as in the case of a condenser in a telegraph circuit (Sec. 21); or it may be transient; or, in the case of alternating-current circuits, it may be periodic. In consequence of this property of storing electrical energy, condensers can be used in numerous ways to alter or modify the characteristics of circuits in some desired manner, such as to change the relative phase of e.m.f. and current in an alternating-current circuit, improve the power-factor, or to prevent the flow of continuous current simultaneously in the same circuit with an alternating current.

PLATE CONDENSERS

156. Types and limits of size. Plate condensers are made commercially in a number of types, usually designated by the kind of dielectric employed. The earliest type, still used in laboratory and class-room work, is the **Leyden jar**, which is merely a two-plate condenser with a glass dielectric, constructed in the form of a wide-mouthed bottle or jar with tin-foil coatings inside and out. Other types of simple plate condensers are made

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with various dielectrics, such as air, mica or paper. Increase of capacity is obtained by building up alternate layers of conductor (plate or sheet) and dielectric; alternate sheets or plates are connected in parallel to the two respective terminals. **Rolled condensers** are constructed as a rule of tinfoil and paper, rolled or folded over a mandrel instead of being laid up in flat sheets or stacks.

In the Mansbridge* self-sealing condenser, foiled paper is used which makes it possible to obtain a high capacity for small volume. Before being assembled into the condenser the foiled paper is tested out electrically by running the paper over a metal roll, with the foiled side uppermost, and applying a constant e.m.f. between the foil and the roller. Any weak spots are thus burned out.

The capacity of a Leyden jar is only a very small fraction of a microfarad. Plate or rolled condensers are made in various commercial sizes from a few hundredths of a microfarad up to several microfarads. Condensers having capacities as large as 100 microfarads, for experimental work, have been arranged by connecting a large number of small units in parallel.

157. The seat of stored energy in a condenser is in the dielectric. The storage of energy is a consequence of the dielectric displacement, or electric charge in the dielectric, which accompanies or co-exists with a state of electric stress. This displacement is expressed

$$D = \frac{k}{4\pi} E \qquad \text{(statcoulombs)} \qquad (54)$$

where D is the electric displacement or charge, in statcoulombs per cu. cm., k is the dielectric constant or specific inductive capacity, and E is the potential gradient in statvolts per centimeter; the prefix "stat" implies units in the c.g.s. electrostatic system (Sec. 1).

158. Limits of voltage. When the electric stress is increased indefinitely, a point is reached at which the dielectric becomes unable to sustain the intensity of stress, and electric rupture occurs, that is to say, the dielectric breaks down. The rupture limit is termed the ultimate dielectric strength. This limit is not a constant quantity under all circumstances, for a given material, but is affected by the shape, size, physical condition, temperature, etc., and by the manner in which the stress is applied. The properties of dielectrics are treated in Sec. 4, under "Insulating Materials." The following table (Par. **159**) gives the properties of some of the dielectrics commonly used in condensers.

159. Table of Properties of Condenser Dielectrics
(Phillips Thomas)

Material of dielectric	Specific inductive capacity	Per cent. power-factor	Breakdown strength, volts per mill
Mica	5.5– 7.5	0.05–0.11	700–1200
Para. paper	2.0– 3.3	0.10–3.00	400–700
Bakelised paper	4.5– 6.0	0.10–4.20	300–700
Celluloid	4.2–16.0	0.70–8.00	400–900
Aceto-cellulose	4.5– 6.5	0.70–1.10	400–700
Gelatine	4.0– 6.0	0.77–8.00	400–800
Kerosene	1.9– 3.6		

These values hold only for sine-waves at 60 cycles per second, at about 20 deg. cent.

160. Calculation of required dimensions of plate condensers. The dimensions of a plate condenser are determined by the formula

$$l = \sqrt{\frac{CL_t}{2.24Nk}} 10 \qquad \text{(sq. in.)} \qquad (55)$$

*Mansbridge, G. F. "The Manufacture of Electrical Condensers;" *Journal of Proceedings* of the Institution of Electrical Engineers, 1908, Vol. XLI, p. 535.

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where L_t is the dielectric thickness in inches, after impregnation, between each pair of metal strips; N is the number of such dielectric strips in the condenser; C is the desired capacity in microfarads; k is the specific inductive capacity of the paper after impregnation, and l is the short dimension of the foil (Fig. 51). This construction insures the lowest possible internal ohmic resistance and also permits the use of extremely thin metal foil.

161. Internal losses and leakage. A condenser may have internal losses of two kinds. The first is due to the **resistance of the plates** themselves, and this is most prominent in rolled condensers of very thin tin-foil, inasmuch as each plate is one long continuous strip and the resistance of the whole strip from outer terminal to inner end may be appreciable. The second kind is the loss in the dielectric itself, due to **dielectric hysteresis**, so-called (Sec. 4); this loss can be expressed as an equivalent series resistance, which should be added to the resistance of the plates. Both forms of resistance absorb energy and reduce the normal angle of lead of current with respect to terminal e.m.f. from 90 deg. to some lesser angle; this is equivalent to saying that the power-factor is increased from a value which is theoretically (or in the ideal case) zero to some definite value, although not usually large.

Besides these two forms of loss, there also may be a pure conduction current flowing through a condenser, in phase with the terminal e.m.f., which results from the lack of perfect insulation, or the presence of leakage. The resistance of the condenser to a continuous e.m.f., after the steady state has been reached, is termed the **insulation resistance.** The value of insulation resistance, of course, should be as high as possible.

162. The power-factor of a condenser determines to what extent it will be heated when used in alternating-current circuits. The power-factor is the cosine of the angle by which the current leads the impressed voltage, with simple sine-wave forms. It varies with the frequency and impressed voltage, with the temperature of operation, and with the dielectric used. The power-factor of a condenser may be determined by measuring the energy loss or by measuring the variation from 90 deg. phase angle directly.* The specific inductive capacities, power-factors, and breakdown strengths of some materials suitable for condenser dielectrics are given in Par. 189. The constants of kerosene oil are included for comparison. The values given hold only for 60-cycle circuits, at about 20 deg. cent. The breakdown sine-wave strengths are in effective (root-mean-square) volts per mil thickness of dielectric. In connecting condensers in series for use on high-voltage circuits (static voltmeters and the like), it is important to know the several power-factors, as the distribution of voltage is affected thereby. The voltage distribution among the several condensers will be proportional to the product of capacity by power-factor, for small power-factors.

163. Absorption of charge. Many dielectrics do not become fully charged instantaneously, nor do they, when fully charged, give up their complete charges instantaneously. The time lag in receiving full or complete charge is usually referred to as absorption. It is noticeable in testing such dielectrics as glass, rubber, gutta-percha, etc. The effect of absorption on the phase of the current is equivalent to resistance in series with capacity.

164. Glass condensers are made both in the form of Leyden jars, and in flat plates. Glass-plate condensers are commonly made of the best plate-glass with sheets of tin-foil shellaced to each side of the plate. The edges of the surface of the plate, not covered with the tin-foil, are varnished to prevent leakage. The finished plates are mounted in a rack and connected together by flat springs which touch the foil of adjacent plates. Condensers of this class are employed on the transmitting side of wireless telegraph apparatus.

L. W. Austin† summarizes the results of his tests as follows: The losses in the **compressed air condenser** used, at a pressure of 15 atmospheres, amount to an equivalent resistance of between 0.1 and 0.2 ohms. Condensers in which "brushing" (brush discharge) is prevented by the nature of their construction show no change in resistance between the limits of observation.

* Grover, F. W. "Simultaneous Measurement of the Capacity and Power Factor of Condensers;" Bulletin of the Bureau of Standards, 1907, Vol. III, p. 371.

† Austin, L. W. "Energy Losses in some Condensers used in High-frequency Circuits;" Bulletin of the Bureau of Standards, 1912, Vol. IX, p. 73.

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4,000 to 20,000 volts, indicating that the internal losses are independent of the voltage. Leyden jars of commercial types immersed wholly in oil show losses but slightly greater than those of the compressed-air condenser. The paper and micanite condensers measured show very much larger losses. The resistances of the different Leyden jars in air vary between 1 and 1.8 ohms at 14,500 volts. Between 10,000 and 20,000 volts the equivalent resistance increases approximately in proportion to the square of the voltage. Placing Leyden jars in series parallel, the capacity remaining the same, does not diminish their brushing losses below 20,000 volts. Immersing only the edges of the conducting coatings of Leyden jars in oil gives an equivalent resistance midway between that observed when wholly in air and that when wholly in oil. Brushing losses are much increased by any semi-conducting material on the surface of the glass at the edges of the conducting coatings of Leyden jars.

165. Mica condensers. Those condensers in which mica is employed for the dielectric are more constant in their properties than those made with paper. Therefore, mica condensers are used as **laboratory standards** of capacity; and also where high voltage is used, on account of the greater dielectric strength of mica. H. L. Curtis has shown* that with good mica condensers the capacity as measured with continuous e.m.fs. does not differ from the capacity as measured with alternating e.m.fs. more than 0.1 per cent., for any frequency; the difference is usually less than 0.1 per cent. For the effect of temperature on mica condensers, see Par. **167**. R. Appleyard has shown† that with mica condensers the capacity remains constant with increasing temperature, but the safe voltage limit decreases.

166. Paper condensers. According to Mr. Phillips Thomas, plate condensers are made most conveniently and economically as follows: strips of metal foil and squares of unglazed paper of close texture and short fibre

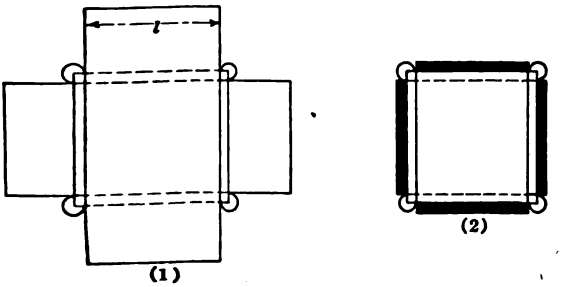


FIG. 51.—Showing the process of building up a multiple-plate condenser.

are piled up in alternation, allowing the metal strips to project on all four sides of the square centre portion. These projecting ends are folded down and melted into one solid bar. The whole is then vacuum dried and impregnated with paraffin, beeswax or the like, and cooled under a pressure not exceeding 10 lb. per sq. in. Fig. 51 shows the method of placing the sheets of foil and paper. The paper sheets are best made in square form, each edge being slightly wider than the narrow dimension of the metal foil. Fig. 51 shows four fibre or wooden upright pegs forming a jig, used in building such condensers. A strip of metal foil is laid one way between the pegs, then a square piece of dielectric (paper) is laid over the strip of foil (the pegs are recessed to fit) and next a second piece of foil is laid between the pegs, at right angles to the first. This constitutes one element

* Curtiss, H. L. "Mica Condensers as Standards of Capacity;" Bulletin of the Bureau of Standards, 1910, Vol. VI, p. 431.

† Appleyard, R. "Dielectrics;" *Philosophical Magazine*, 1896, Vol. XLII, p. 148.

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of the condenser. This process is repeated until as many sheets of dielectric as desired have been used, after which the projecting sheets of foil are rolled up and melted into a solid bar, as in (2). The condenser is then ready for impregnation.

167. Effect of Temperature on Paraffin-paper and Mica Condensers* (Abst. from Proc. I. E. E., 1896, Vol. XXV, p. 723)

Temp. deg. cent....		0.4	12.5	20.1	26.9	32	37.8	43.3
Paraffin paper.	*R*	17,740	7,216	3,622	1,947	1,231	792	551
	C	0.98	0.98	0.98	0.98	0.97	0.96	0.95
Mica.....	*R*	31,427	28,427	22,000	16,272	17,010	15,270	10,521
	C	0.5	0.5	0.5	0.5	0.5	0.5	0.5

R = effective series resistance, in ohms. *C* = capacity in microfarads.

168. Table of Commercial Ratings and Sizes of Telephone Condensers (Paraffin paper, rolled type, commercial telephone condensers)

Capacity (mf.)	Dimensions			Safe maximum effective voltage	
	Length (in.)	Breadth (in.)	Thickness (in.)	Continuous (volts)	Alternating (volts)
0.05	4.44	1.75	0.94	.....	1,200
0.10	4.44	1.75	0.94	.....	1,000
0.10	4.44	1.75	0.41	500	.....
0.25	4.44	1.75	1.63	.....	1,000
0.30	4.44	1.75	1.06	750	.....
0.50	4.44	1.75	0.53	.....	.....
0.50	2.38	1.25	0.75	.....	.....
1.00	4.44	1.75	0.94	500	.....
1.00	3.00	2.38	1.00	.....	.....
1.00	8.72	6.25	1.48	.....	1,000
1.50	4.44	1.75	1.63	500	.....
2.00	4.44	1.75	1.63	500	.....
2.00	4.38	2.06	1.13	.....	.....

It should be kept in mind in considering the above dimensions that the capacity varies directly as the area of the plates and inversely as the distance between them (thickness of dielectric or insulation). Hence the volume per unit of capacity increases rapidly as the safe maximum working voltage increases. Condensers of the rolled paper type are not as a rule tested at less than 500 volts, continuous e.m.f. The insulation resistance should be so high that the leakage is entirely negligible in comparison with the charging current.

169. Condensers for use with induction coils and, in general, condensers shunted across gaps to minimize sparking, are usually of the plate type, since it is difficult and expensive to construct rolled condensers having sufficiently low ohmic resistance in their conducting plates. The table of dimensions (Par. **174**) applies to condensers used with induction coils.

170. Static condensers for correcting power factor. Condenser sections assembled in oil within metal containers, combined with reactors for each line leg, discharge resistance rods for each phase, a fuse in each condenser section, and a switch for controlling the equipment, is known as a

* See also Grover, F. W., "The Capacity and Phase Difference of Paraffin Paper Condensers as Functions of Temperature and Frequency," Bulletin of the Bureau of Standards, 1911, Vol. VII, p. 495.

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static condenser* for correcting comparatively small loads having low power factors, in a manner similar to which synchronous condensers (Par. 186) are used in large systems. The resistance rods very quickly drain off any charge that may be in the condensers when disconnected from the line.

Static condensers may be obtained for installation on circuits ranging in frequency from 40 to 125 cycles and in voltages from 220 to 2,300 volts, in capacities from 60 kv.a. to 300 kv.a. The efficiency in all capacities is at least 99 per cent. At normal capacity the temperature rises of the condenser section and reactors are not over 10 deg. cent. and 50 deg. cent. respectively.

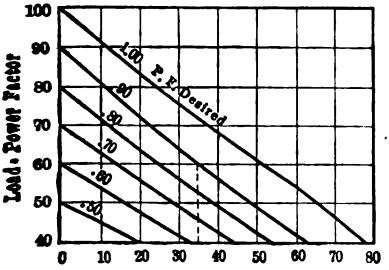


FIG. 52.—Additional capacity obtained by increase of power factor.

Referring to Fig. 52, assume that the load is 250 kw. with 60 per cent. power factor, and that a 90 per cent. power factor is desired. The projection of the intersection of the 60 per cent. power-factor line with the 90 per cent. power-factor curve gives the kw. load at 60 per cent. power factor made available at 90 per cent. power factor as 0.358×250 kw. = 89.5 kw.

171. **Encased mica condensers** are used for phase shifting as well as for line and apparatus protection, but they are particularly adapted for use in radio transmission systems. The Dubilier Mica Condenser, extensively used by the Army and Navy, consists of several units comprising alternate sheets of mica and foil piled on top of one another in an aluminum casing. Each unit is separated from the next by a sheet of mica. The complete condenser contains over a thousand sheets of mica and foil.

After all moisture and air are expelled, an insulating adhesive is forced through the entire condenser. The casing then is filled with a melting compound and a pressure plate is inserted. Then the insulating cover is screwed on. A terminal passes through the cover; the aluminum case constitutes the other terminal. It is claimed that this condenser has an efficiency of more than 90 per cent. when operating in a standard radio transmitting set at 500 cycles and 12,500 volts, and that it can withstand 100 per cent. overload.

172. **Measurements of capacity of condensers.** When possible, condensers should be tested with the same e.m.f. that will be applied to them in practical use. In alternating-current tests, this should include the same voltage, frequency and wave-form. For methods of measuring capacity see Sec. 3. Direct-current tests usually indicate greater capacity than alternating-current tests due to the phenomenon of electric absorption. For this reason the alternating-current capacity increases slightly with decrease in frequency.

173. **Ratings of commercial paper condensers.** A 2-mf. condenser made by one American manufacturer, using paraffin paper, is 4.5 in. long, 2 in. wide and 1 in. thick, and the pre-war price was about 55 cents. The

* General Electric Co., "Static Condensers," Bulletin No. 49714A, April, 1919.

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volume per microfarad is 4.5 cu. in. The rated voltage limit is 400 volts, alternating; one of these condensers failed on test at 650 volts, alternating. The energy loss was from 1 per cent. to 2 per cent. Another condenser of the paper type,* built to stand 10,000 volts (alternating), occupied 2 cu. ft. per microfarad. Generally speaking, the ordinary paper condensers of the rolled type used in telephony and telegraphy are built to stand about 500 volts, alternating, and range in size from a few hundredths of a microfarad up to 4 mf. to 6 mf.; some of these condensers are built to stand 1,000 volts, alternating. The higher the voltage limit, the more bulky and expensive the condensers become. The table (Par. **168**) gives the sizes, dimensions, voltage limits, and approximate costs of rolled paper condensers used in telephone practice.

174. Table of Dimensions of Condensers Used with Induction Coils (Ehnert)†

Spark-length, cm	5	10	15	20	25	30	35	50
No. of layers	60	65	70	75	80	90	100	150
Dimensions of tin-foil sheets, cm.	15 by 10	17 by 10	22 by 10	22 by 11	25 by 13	25 by 17	27 by 20	33 by 23

ELECTROLYTIC CONDENSERS

175. Elements of electrolytic condenser. Certain metals such as aluminum, magnesium, and tantulum, when immersed in an electrolyte, possess the property of allowing electricity to flow in one direction and not in the other, providing a certain critical value of e.m.f. is not exceeded. Two electrodes of this kind practically prevent all flow of electricity and constitute a condenser which is known as an electrolytic condenser. Such condensers are usually constructed with aluminum electrodes and can be made in large units at a cost well within commercial economic limits. The greatest disadvantage of the aluminum electrolytic condenser, as compared with dry condensers, is that it has an appreciable energy loss. Electrolytic condensers used as lightning arresters are usually connected in series with a spark gap so as to avoid the energy loss which would exist were the line voltage continually impressed across its terminals.

176. The critical voltage of an electrolytic condenser is the maximum value of impressed e.m.f. which it will stand without permitting an appreciable leakage current. The table in Par. **177** gives the critical voltages for aluminum electrodes with different electrolytes.

177. Critical Voltages for Aluminum and Various Electrolytes
(*Electrochemical & Metallurgical Industry*, Vol. VII, p. 216, 1909)

Na_2SO_4	40	KCN	295	NH_4HPO_4	460
$KMnO_4$	112	NH_4HCO_3	425	Ammonium citrate	470
$(NH_4)_2CrO_4$	122	Na_2SiO_3	445	$Na_2B_4O_7$	480

178. The valve effect of the aluminum anode is due to an exceedingly thin oxide or hydroxide film on the aluminum plate, covered by a thin gas layer, the resistance of which per square centimeter amounts to millions of ohms. Such an anode may be considered as a condenser. In comparing such an anode to an ordinary solid condenser, the gas layer corresponds to the dielectric, while the aluminum electrode and the electrolyte correspond to the two plates of the condenser.

* Mordey, W. M. "Some Tests and Uses of Condensers;" *Journal of Proceedings* of the Institution of Electrical Engineers, 1909, Vol. XLIII, p. 618.

† Ehnert, E. W. "Theorie und Vorausberechnung der Funkeninduktoren;" *Elektrotechnik und Maschinenbau*, 1907, Vol. XXV, pp. 337, 361 and 377.

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179. The capacity of this condenser depends only upon the voltage of formation and the material of the anode, and is independent of the nature of the electrolyte. Fig. 53 gives the capacity as a function of the formation voltage for aluminum, tantalum and magnesium. The abscissas are the voltage of formation, the ordinates, the capacity per square centimeter of surface. The second set of curves in Fig. 53 shows the increase of the calculated ratio (t/k) of thickness of the gas layer to the specific electrostatic capacity with increasing formation voltage.

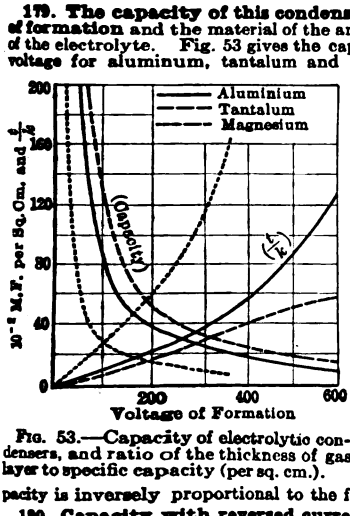


FIG. 53.—Capacity of electrolytic condensers, and ratio of the thickness of gas layer to specific capacity (per sq. cm.).

By passing from lower to higher voltages the thickness of the gas layer increases and assumes its new value within a few minutes. In passing back from higher to lower voltage, however, it requires months before the thickness of the gas layer is reduced again to its former value. For short experiments the thickness of the gas layer may be considered as constant as long as the voltage remains below the voltage at which the anode was formed. In this case the electrolytic condenser behaves like a condenser with interchangeable dielectric. However, if the formation voltage is increased, the capacity is inversely proportional to the formation voltage.

180. Capacity with reversed currents. An electrolytic condenser has not necessarily the same capacity in opposite directions of the current. To insure equal capacity in both directions, both electrodes must have an equal surface in the electrolyte and must be formed at the same voltage.

181. Precautions in manufacture. In the practical manufacture of electrolytic condensers, attention is paid to the fact that the oxide film and the gas layer adherent to it cover only those parts of the aluminum electrode which are in the electrolyte. From those points of the aluminum surface which are just above the electrolyte, the electricity tends to jump or arc from the aluminum plate into the electrolyte, causing considerable heat and corrosion of the aluminum. It is, therefore, important to make this aluminum boundary line between electrolyte and air as short as possible and to insulate it very carefully.

182. Electrolytic condensers for alternating-current circuits should be formed with continuous e.m.fs., equal to the maximum value of the alternating e.m.f.

183. The energy losses are small at low voltages and do not increase appreciably when the condenser is connected in the circuit for a long period of time, but as the voltage is increased the losses increase with time at an increasing rate. In cases where condensers are to be used continuously, it is advisable to connect several low-voltage condensers in series. Dr. Gunther Schulze* carried out an extensive investigation of electrolytic condensers in the Reichsanstalt which was described and discussed in an article: "Aluminum Electrolytic Condensers of High Capacity," published in *Electrochemical and Metallurgical Industry*, Vol. VII, p. 216 (1909).

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RESISTORS AND RHEOSTATS

BY LEONARD KEBLER

TYPES OF RHEOSTATS

185. Plate-type rheostats have a resistance in the form of a reflexed metal wire or ribbon attached to a plate of porcelain-covered iron, or to a plate of insulating material such as soapstone, by means of a coating of fused enamel or by cement. They are used almost universally for small field rheostats, theatre dimmers, small motor-speed controllers, battery charging rheostats, etc.

186. Box-type rheostats have a resistance in the form of wire-wound, enamel-covered porcelain tubes; cast-iron grids; coils of bare wire; metallic ribbon; carbon discs, or a conducting liquid. They are used for large field rheostats, motor starters, large motor-speed controllers, battery-charging rheostats of the larger sizes, etc. (Also see Par. **199**.)

FIELD RHEOSTATS

187. Field rheostats are used in series with the fields of dynamos for regulating the field strength and in turn the voltage of the dynamo, or in the fields of motors for varying the field strength and in turn the speed.

188. Generator field rheostats for direct-current machines usually are provided with such a value of total resistance that it is about equal to that of the field to be regulated, thus giving a variation in field strength from maximum to one-half maximum with a constant exciting voltage.

Alternating-current generators have field rheostats whose resistance is usually about twice that of the field, thus giving a variation in field amperes from maximum to one-third maximum, at constant voltage.

189. Motor field rheostats have resistances of a value determined by the control desired. The resistance is about equal to that of the field when 25 per cent. speed increase is wanted and may be eight or ten times that of the field when about 400 per cent. increase is wanted.

190. The current capacity of a field rheostat should change by an equal amount as each additional step of resistance is inserted. If I_{max} is the current when the rheostat is short-circuited, I_{min} the current when all resistance is in circuit, N the total number of steps and IN the change in amperes per step, then

$$IN = \frac{I_{max} - I_{min}}{N} \quad \text{(amp.)} \qquad (56)$$

and the current I_n when n steps are in circuit is

$$I_n = I_{max} - nIN \quad \text{(amp.)} \qquad (57)$$

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The total resistance of the rheostat when n steps are in circuit is

$$R_n = \frac{E}{I_{max} - nI_n} \quad \text{(ohms)} \qquad (58)$$

and when $(n-1)$ steps are in circuit the total resistance of the rheostat is

$$R_{n-1} = \frac{E}{I_{max} - (n-1)I_n} \quad \text{(ohms)} \qquad (59)$$

The resistance of the nth step is therefore $R_n - R_{n-1}$ ohms. In each case E is the e.m.f. in volts at the terminals of the field circuit.

191. The maximum number of watts to be dissipated by any one step will be approximately constant, if the change in amperes per step of resistance inserted is constant, and the resistance of each step is figured as above.

192. The maximum allowable temperature rise for field rheostats is 350 deg. cent. when measured by a thermometer placed against the resistive conductor. The limiting observable temperature rise for the issuing air is 175 deg. cent. measured one inch from the enclosure about the resistor.

193. The automatic-release feature on motor field rheostats is sometimes provided. This usually consists of a magnetic device connected across the armature terminals which short-circuits the rheostat resistance when the motor stops, so as to prevent starting under weakened field.

MOTOR SPEED-REGULATING RHEOSTATS

194. Speed-regulating rheostats for main armature circuits have varying amounts of resistance for varying conditions.

195. The required resistance for a certain per cent. of speed reduction, with a constant-potential **shunt-wound motor**, is determined as follows: Let S be the normal speed in r.p.m., S_r the reduced speed in r.p.m., E the line voltage, I the current taken at reduced speed, R the rheostat resistance in ohms required to secure the desired speed reduction then

$$\frac{S}{S_r} = \frac{E}{E - IR} \qquad (60)$$

$$E - IR = \frac{ES_r}{S} \qquad (61)$$

and $$R = \frac{E}{I}\left(1 - \frac{S_r}{S}\right) \qquad (62)$$

196. Motor current requirements at reduced speed. For pump, machine duty, etc., the current taken at reduced speeds is approximately that at normal speed. For large ventilating fans the torque varies as the square of the speed, but for ventilating fans of less than 20 h.p., the current will vary more nearly as the speed.

197. Temperature rise of plate-type rheostats. For each watt dissipated per sq. in. of free radiating surface, the rheostat plate will rise about 60 deg. cent., and usually but one side of a plate-type rheostat can radiate freely. Therefore where A is the area of one side of the rheostat (sq. in.), I the current flowing (amp.) and R the resistance of the rheostat (ohms) in circuit, the temperature rise will be 60 (I^2R/A) in deg. cent. (approx.).

198. The maximum allowable temperature rise for speed regulating rheostats is the same as for field rheostats given in detail in Par. **192**.

199. Calculations of resistance, current-carrying capacity, etc., for box-type rheostats, regardless of the use to be made of them, may be carried out in the same manner as for plate-type rheostats.

200. Automatic features on armature speed controllers consist of no-voltage protection, overload protection and overload circuit-breaker. No voltage protection and overload protection are secured by the use of contact arms which are held in the operating position against the action of a spring. On no-voltage or overload the spring is magnetically released and moves the arm to the open-circuit position.

An overload circuit-breaker on armature speed controllers consists of a separate switch arm held closed by a latch. On overload this latch is tripped by a magnet, the switch is opened by a spring and breaks the main-line circuit irrespective of the movement of the resistance controlling arm.

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201. Speed regulators for series-wound motors. For series motors the calculation of the exact resistance for a definite speed variation requires a curve of the motor characteristics. Lacking this it will be found that a controller designed as above for a shunt machine (Par. 195) will give approximately the same regulation for a series machine running under constant-torque conditions.

THEATRE DIMMERS

202. Theatre dimmers are made of a number of plates mounted in a bank and each plate controlled by its own lever. **A master lever** is usually arranged with cams so that it may control all or any number of the plates

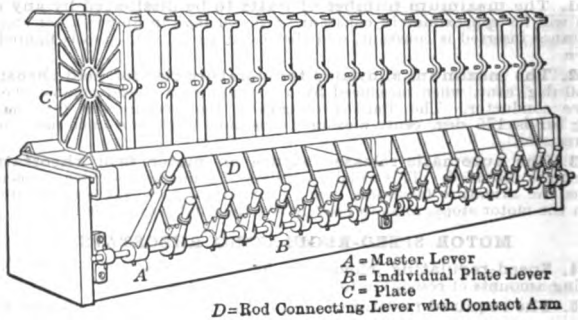


FIG. 54.—Bank of theatre dimmers.

at once. A typical bank is shown in Fig. 54. The circuit operated by one plate seldom carries more than 50 amp. except in the case of the dimmer for the auditorium lights. The latter often carries 300 to 400 amp.

203. For dimming carbon-filament lamps a resistance equal to about 3.4 times that of the lamps in the circuit at full candle-power will dim sufficiently so the lamps have no illuminating power. In order that the dimming may be done smoothly and without flicker, 50 steps are required.

204. For dimming tungsten-filament lamps to a point where the filament is just visible in the dark, a resistance equal to 3.6 times the resistance of the lamp load at full candle power is required. This reduces the current flowing to 25 per cent. of normal. To dim the lamp to blackness, a resistance equal to 4.6 times the resistance of the lamp load at full candle power is required, which will reduce the current to 18.7 per cent. of normal. In order that the lamps shall be dimmed smoothly and without flicker, the dimmer must have at least 110 steps.

205. Free ventilation of theatre dimmers is essential, as the amount of heat radiated by a complete equipment is often large.

206. Overloads caused by using too many lamps, or lamps of larger candle-power than the dimmer is designed for, must be carefully avoided.

RESISTORS FOR MOTOR STARTERS

207. Motor-starting resistors should be so proportioned that the total resistance and the resistance per step admit sufficient current to start the motor, but not to exceed certain limits.

208. The normal current is that necessary to keep the motor armature turning over after it is once started, and is less than the current required to overcome the torque plus the friction of rest in starting from standstill.

209. The starting current is equal to the normal current plus a current necessary to overcome the friction of rest at starting, overcome inertia and produce the desired rate of acceleration. In general the starting current is assumed to be one and one-half times the normal current.

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The current flowing at the time the starting rheostat establishes the circuit, is limited not only by the resistance of the motor starter but also by the resistance of the armature of the motor, the resistance of the line, the inductance of the motor armature, etc. During the time the inductance of the motor armature is dying down, the motor armature itself is speeding up and generating counter voltage, so that the resistance necessary in a motor starter is in general 70 per cent. of that which would be necessary if this resistance were the only factor to be considered.

210. Rating of resistors for motor starters. The resistors of motor starters are in general rated as for light starting duty or for heavy starting duty.

211. Light starting duty resistors must not exceed the temperature rises of Par. **192**, if used for starting up a motor once every four minutes for an hour, taking 15 seconds each time for starting, with an average current of 125 per cent. of normal current.

212. Heavy starting duty resistors must not show a temperature rise greater than that in Par. **192**, if used for starting up a motor once every four minutes for an hour, taking 30 seconds each time for starting, with an average current of 125 per cent. of normal current.

213. The resistive conductor is usually in the form of wire, ribbons, or cast iron grids, and mounted in some substantial manner as next described.

214. Supports for resistive conductors are tubes of porcelain or asbestos or other insulating material when the resistive conductor is wire or ribbon, and usually under these circumstances the resistor is enclosed in a sheet iron case. When cast-iron grids are used they are usually mounted in a separate case and connected by cables to the starter face plate.

BATTERY-CHARGING RHEOSTATS

215. The resistance of a battery-charging rheostat, for charging storage batteries from a constant-potential source, may be determined as follows: If E is the e.m.f. of the charging circuit (volts), E_{min} the lowest e.m.f. of the battery during charge (volts), I_{min} the lowest value of charging current, then the total rheostat resistance R will be

$$R = \frac{E - E_{min}}{I_{min}} \quad \text{(ohms)} \qquad (63)$$

A certain amount of this resistance must carry the maximum charging current I_{max}; this amount is

$$R = \frac{E - E_{min}}{I_{max}} \quad \text{(ohms)} \qquad (64)$$

The balance of the resistance will have a current carrying capacity varying from I_{max} to I_{min}.

216. Lead-cell batteries normally have a voltage per cell of at least 2 volts after charging is started, so that in calculating rheostats for lead cells E_{min} referred to in Par. **215** is equal to the number of cells multiplied by two.

217. Edison-cell batteries normally have a voltage of at least 1.40 volts per cell after charging is started, so that in calculating rheostats for Edison cells E_{min} referred to in Par. **215** is equal to the number of cells multiplied by two.

218. Carbon battery-charging rheostats have a resistance that varies inversely as the pressure and may be increased to any extent desirable by loosening the pressure on the carbon discs. For this reason the total amount of resistance necessary in the rheostat need not be considered in designing a carbon rheostat.

MISCELLANEOUS RHEOSTATS

219. Wire rheostats. Wire can be wound in coils, or stretched over insulated frames. Wires larger than No. 6 A.W.G. are difficult to wind in spiral form and wires smaller than No. 21 A.W.G. must be wound upon an insulating core. When it is desired to increase the current capacity of a coil resistor beyond that of No. 6 wire, several coils may be connected in multiple. The table in Par. **220** gives the mechanical dimensions of coils made of different sized wires.

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220. Table of Dimensions of Wire Coils for Rheostats

Size, A.W.G.	Max. mandrel, inches	Feet per turn	Turns per inch	Max. coil length, inches
6–8	1.25	0.38	4.0	18
9–11	1.00	0.30	4.5	12
12–14	0.75	0.23	7.0	12
15–18	0.50	0.16	9.0	12
19–21	0.25	0.082	14.0	6
22–30	Must be wound on insulated core			

Note.—The maximum diameter of mandrel given in the table corresponds to the length given therein, and if a stiffer coil is desired a smaller mandrel must be used.

221. Mounting of wire coils. The finished coils are generally mounted in an iron frame. They are suspended vertically from insulated supports and interconnected so as to give the proper current capacity, and resistance. The total resistance should be divided into units containing a sufficient number of coils in multiple to give the required current capacity and then enough of these units in series to give the required resistance. The terminals of each unit should be brought out and so arranged that the unit can be cut out or short-circuited when it is desired to vary the resistance.

Only fire-proof material should be used in construction of the rheostat. Resistors which are not used continuously, such as starters, etc., can have their heat capacity considerably increased by using plenty of heat-conducting material, which will delay the attainment of the final temperature. The heat capacity and effective radiating surface of a coil resistor can be increased by placing the coils in an iron box filled with sand, oil or some other insulator which is a fair conductor of heat. Coils may be submerged, temporarily, in water when it is desired to increase their capacity for some special purpose. Wire under these conditions can be worked at about four times its normal capacity.

222. Radiation. When coils are to be enclosed in a weather-proof box, 0.5 sq. in. to 1 sq. in. of box surface should be allowed per watt dissipated by the resistor. With a good ventilation and about 1 sq. in. per watt the temperature rise will be about 100 deg. fahr. See Par. **197.**

Wires which contain zinc should not be used where the resistor is likely to be overheated, because they will become brittle.

223. Water-cooled rheostats for generator tests. Rheostats made up of galvanized iron wire mounted on wooden frames and submerged in running water are often used to absorb energy when making acceptance tests of large apparatus in the power house. In this case the power dissipated can be assumed as directly proportional to the surface of the resistor.

224. Carbon rheostats of the compression type have the advantage of fine adjustment. These rheostats are generally made up of plates held in a frame and the resistance varied by varying the pressure between the plates with a screw clamp. Carbon has a negative coefficient of resistance change with temperature. Carbon-filament incandescent lamps, if heated appreciably, do not make satisfactory rheostats because of the rapid change of resistance with current changes.

225. Carbon rheostat resistance varies inversely as the pressure, so that any desired resistance within limits can be secured if the pressure is lessened or increased sufficiently. Such rheostats are used for laboratory tests and similar experimental work where the currents to be handled are not large and where it is not necessary to hold the resistance constant during changes in temperature of the rheostat.

226. Liquid rheostats are especially adapted to the absorption of large amounts of power and are often used as an artificial load in testing dynamos or as starting rheostats for large motors starting under load. The adjustment

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is perfectly continuous, but unless there is a provision for short-circuiting the electrodes outside the solution it is impossible to cut out the resistance entirely.

227. Electrodes for liquid rheostats. The electrode material is not important so long as it is a good conductor and is not attacked by the liquid. Lead or carbon plates are used with sulphuric acid, copper with copper sulphate, and iron in most other cases. The **current density** should not exceed 1 amp. per sq. in.

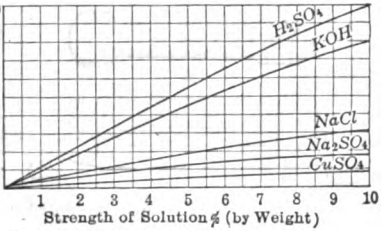


FIG. 55.—Conductivity of solutions.

228. The solution depends upon the voltage and upon the quantity necessary to radiate the heat. Pure water is seldom used for pressures under 1,000 volts. For voltages below this, sulphuric acid, or some salt is added to the water to increase its conductivity.

Fig. 55 shows the relative conductivity of various solutions expressed in inches between the plates with a current density of 1 amp. per sq. in. Ordinary water gives a drop from 2,500 to 3,000 volts per in. gap at this current density.

RESISTOR UNITS

229. Resistor units are used wherever a resistor that is not variable is desired. These units are made in many forms and types for the use of those who desire to purchase the units and assemble them in rheostats; for use in the speed regulators of desk and ceiling fans; for testing purposes, etc.

230. The resistance material is usually of German silver or some similar material of low temperature coefficient. This is usually wound on tubes and is then covered with a cement-like coating or with a fused vitreous enamel. The tubes on which the wire is wound consist of pottery, asbestos paper, lava, etc. Pottery tubes are used when the resistance wire is to be hermetically sealed in a fused vitreous enamel.

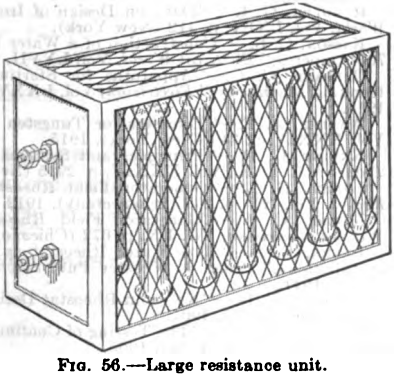


FIG. 56.—Large resistance unit.

231. Carbon resistance units are sometimes used where exceedingly high resistances with a very low watt dissipating capacity are desired.

232. The watt dissipating capacity (I^2R) of such tubular units as are commercially manufactured and listed, varies from 1 to 300 watts. The resistance of these units can be made as high as 16,000 ohms on an enameled wire wound tube 4 in. long and ¼ in. diameter.

233. Large resistor units are made of cases enclosing a number of the tubular units described in Par. **230**, or enclosing cast-iron grids, German silver ribbon, etc. (See Fig. 56.)

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234. The temperature rise of resistor units is as discussed in Par 192.

235. Mounted resistor units are manufactured with various attachments for readily mounting in special apparatus or for giving various com-

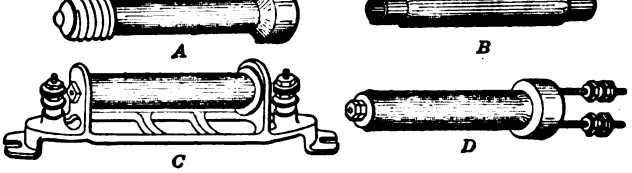


FIG. 57.—Mounted resistor units.

binations, etc. Units designed to replace resistance lamps in order that a resistance may be secured that does not change with time, or on account of heat, are so made as to screw into a standard Edison socket. (See A, Fig. 58.) Other units are made with ferrules on the ends, so they may be readily inserted in the conventional type of fuse clips (See B, Fig. 58); still others are mounted in brackets (See C, Fig. 57); on porcelain bases See D, Fig. 57), etc.

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SECTION 6

TRANSFORMERS AND RECTIFIERS

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SECTION 6

TRANSFORMERS

INTRODUCTION

1. A transformer is a device for transferring energy in an alternating-current system from one circuit to another. It consists essentially of two independent electric circuits linked with a common magnetic circuit. Thus energy at low voltage may be transformed to energy at high voltage, or *vice versa*. In like manner, current of a given value in one circuit may be transformed into current of another value in a different circuit. The winding of the transformer connected to the supply circuit is referred to as **the primary winding**, and those windings of the transformer that are connected to the receiver circuits are referred to as **secondary windings.**

2. If a transformer with open secondary winding has its primary circuit connected across alternating-current supply mains, only a small current will flow through the primary. This current is alternating and produces an alternating magnetic flux in the iron core of the transformer, which interlinks both the primary and the secondary windings and by its rate of change induces an e.m.f. in each. If the two windings are closely associated with each other, the e.m.f. induced in each will be proportional to their respective numbers of turns. The e.m.f. induced in the primary winding is known as the **counter e.m.f.** of self-induction of the primary, or **back e.m.f.**, and is equal in magnitude to the e.m.f. of the mains less the IR drop due to the current passing through the winding. Therefore, if the permeability of the magnetic circuit of the transformer is high and the resistance of the primary winding is low, the counter e.m.f. will be very nearly equal in magnitude to the e.m.f. of the supply circuit, and it follows also that the secondary induced e.m.f. will be nearly equal to the e.m.f. of the supply circuit multiplied by the ratio of the number of turns in the secondary winding to that of the primary winding.

3. If the secondary circuit is completed through an impedance or load, current will flow through the secondary and the load; this will tend to demagnetise the core, so that the effective impedance of the primary winding is at once lowered and more current flows into it. The extra current, being just sufficient to overcome the demagnetising effect of the current flowing in the secondary winding, will have the same time-phase as the secondary current and the ratio of the magnitudes of the two currents will be equal to the reciprocal of the ratio of the numbers of turns in the respective windings.

4. The secondary current causes a drop in e.m.f. in the secondary winding, partly due to the resistance of the winding and partly due to magnetic leakage caused by the fact that all of the flux which interlinks the primary turns does not interlink all the secondary turns.

5. The primary current likewise produces a drop of e.m.f. in the primary winding, due to the resistance of the primary winding and to the fact that there is a portion of the magnetic flux which interlinks some of the primary winding without interlinking any of the secondary winding.

6. The induced e.m.f. will therefore be proportional to the e.m.f. of the supply circuit, less the drop in the primary winding; and the secondary terminal e.m.f. will be equal to the secondary induced e.m.f. less the drop in the secondary winding, the drops being taken in their proper phase relation. The total drop from supply e.m.f. to secondary terminal e.m.f. is usually quite small in power transformers, so that the product of the secondary current and terminal e.m.f., measured in kilovolt-amperes, differs from that of the primary by 2 or 4 per cent., only, at full load, while the ratio of the output

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to the input, or commercial efficiency, may be as high as 99 per cent. at full load.

7. **The ratio of transformation is the ratio of primary voltage to secondary voltage,** or very approximately the ratio of primary turns to secondary turns; it is also approximately the same as the ratio of the secondary current to the primary current.

8. **Constant-potential transformers,** or transformers having nearly constant ratio at all loads, are most generally used for transmission and distribution of power; they are then designated power transformers (Par. 85). When used for the purpose of raising the voltage they are referred to as **step-up** transformers, and when used for lowering the voltage are referred to as **step-down** transformers. If it is desired to call attention to the windings of a transformer without considering their relation to the supply circuit they are termed **the high-voltage** winding and the low-voltage winding.

9. **Constant-current transformers** are those in which the current in the secondary or receiver circuit is automatically maintained constant when the primary is connected to a constant-potential source of supply. The mutual inductance varies with the load.

10. **Instrument transformers** are those employed to connect measuring instruments or relays with power mains, the primary being connected to the mains and the secondary connected directly to the instrument. When their function is to transform from the voltage of the supply circuit to a voltage suitable for operating instruments or relays they are termed **shunt-type or potential transformers.** When their function is to transform the current in the supply circuit to a suitable value in the secondary or instrument circuit they are termed **series-type or current transformers.**

11. **Auto-transformers** are those in which the primary and secondary circuits are electrically connected so that part of the load in the receiver circuit is supplied directly from the supply circuit through the primary winding, the remainder being supplied indirectly through the secondary winding by electromagnetic induction.

12. **Transformers may be conveniently classified** as follows:

(a) **Power transformers** for the transmission and distribution of relatively large quantities of energy.

(b) **Instrument transformers** for use with measuring instruments and relays.

(c) **Auto-transformers** for general power purposes, balancing electric circuits, etc.

(d) **Constant-current transformers and regulators,** used for street lighting.

(e) **Voltage regulators,** used for regulating the voltage of alternating electric circuits.

13. **All these different classes of transformers have the same "General Theory,"** which will first of all be discussed: certain considerations in design common to all will next be taken up; and finally the characteristics peculiar to each class will be presented in the order given, together with commercial data.

GENERAL THEORY

14. **The magnitude and direction of the induced e.m.f.** in a circuit are given in the two laws known as **Neumann's Law** and **Lens's Law** (See. 2). If these laws are applied to the case of the transformer on open circuit the following relations are obtained.

$$\left.\begin{aligned} R_1 i_0 + \frac{\partial}{\partial t}(L_1 i_0) &= e_1 \\ \frac{\partial}{\partial t}(M i_0) &= e_2 \end{aligned}\right\} \quad (1)$$

where $(L_1 i_0)$ and $(M i_0)$ are the numbers of interlinkages of tubes of induction with the primary and secondary windings respectively, i_0 is the primary open-circuit or exciting current, R_1 is the resistance of the primary winding, e_1 is the e.m.f. impressed on the primary winding, and e_2 is the e.m.f. induced in the secondary winding.

15. **Practical formulæ for transformers.** If it is assumed that all the turns of the primary and the secondary winding completely encircle

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a magnetic circuit of uniform cross-section and infinite permeability, an that e_1, the instantaneous value of the e.m.f. impressed on the primary, a simple harmonic time-function of the form

$$e_1 = 10^8 \times \sqrt{2} E_1 \cos \omega t \qquad (1$$

where E_1 is the root-mean-square or effective value of the impressed volta and ω is equal to $2\pi f$ where f is the frequency of the alternating e.m. is becomes zero, and the resulting solution of these equations will give

$$\left.\begin{aligned} (L_1 i_0) &= n_1 A_1 B \sin \omega t \\ (M i_0) &= n_2 A_1 B \sin \omega t \end{aligned}\right\} \qquad (2$$

$$E_2 = -\frac{n_2}{n_1} E_1$$

where n_1, n_2 are the number of turns in the primary and secondary windin respectively, E_2 is the effective value of the secondary voltage, A_1 is the cros sectional area of the magnetic circuit and B the maximum instantaneou value of the induction in C.G.S. lines per unit area. The relations betwee E_1 and B are given by

$$\left.\begin{aligned} B &= \frac{\sqrt{2} E_1 \times 10^8}{\omega n_1 A_1} = \frac{E_1 \times 10^8}{4.44 f n_1 A_1} \text{ (c.g.s. lines per unit area)} \\ E_1 &= \frac{\omega n_1 A_1 B}{\sqrt{2} \times 10^8} = 4.44 \frac{f n_1 A_1 B}{10^8} \qquad \text{(volts)} \end{aligned}\right\} (4$$

These are the equations used to determine the value of the open-circu secondary voltage and the induction in power transformers. Even if th reluctance of the magnetic circuit be taken into account the value of B not materially altered, and since exigencies of manufacture may cause large errors in this quantity than that due to the assumption of infinite permeabi ity, greater refinement is useless. The error in the value of E_2 due to thi assumption is not of consequence in most commercial transformers.

16. The primary open-circuit characteristics of power transformer may be obtained with sufficient accuracy by means of a curve giving th **loss per unit mass** of iron at different induc tions (Sec. 4), and another giving the **excitin volt amperes per unit mass** at differen

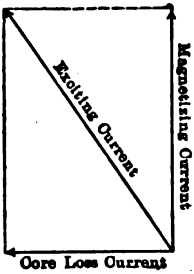


FIG. 1.—Vector diagram of equiva lent sine-wave exciting current.

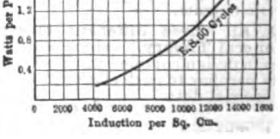


FIG. 2.—Core-loss curve.

inductions. The latter curve is preferably obtained from the average tests on a number of transformers. Sometimes tests are made on differe sizes of transformer cores and the resulting curves plotted separately; this done to take care of the variations due to building, which are greater in sm transformers than in large ones. The value of the exciting current obtain in this manner is known as the **equivalent sine-wave** value. The relati between these equivalent sine-wave values of core-loss current and exci current as obtained above is shown by vector diagram Fig. 1. Typi core-loss and exciting volt-ampere curves are shown in Fig. 2 and Fig. respectively.

17. The current in the primary winding of an unloaded tran former, which has a sine-wave e.m.f. impressed across its terminals, is no

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sine-wave, but has harmonic components. This is due to the variable permeability of iron and to its retentiveness. The study of the wave distortion due to iron magnetic circuits assumes importance in instrument transformers on account of the possible introduction of error thereby. A knowledge of the properties of different kinds of transformer steels is therefore essential to the design of instrument transformers (Sec. 4).

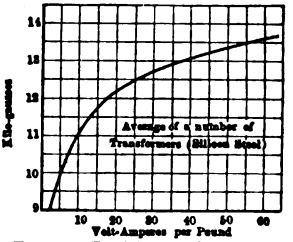


FIG. 3.—Exciting volt-amperes curve.

18. The secondary open-circuit voltage. Referring to Eqs. 1, $L_1 i_0$ and $M i_0$ are variables of time, but L_1 and M should also be considered as variables depending on the instantaneous value of the induction. Then assuming unity ratio of primary and secondary turns,

$$e_2 = -e_1 + R_1 i_0 + \frac{\partial}{\partial t}\{(L_1 - M) i_1\} \qquad (5)$$

where the quantity $(L_1 - M)$ depends on the leakage flux through the windings. This flux will vary directly with the current in the primary, provided that the relative reluctance of different parts of the magnetic circuit remains unchanged throughout the cycle. Hence, if the dimensions of the winding space are large and the permeability of the core is high, even wide fluctuation of value in the latter will produce an inappreciable effect on the total reluctance of the leakage paths. It may therefore be safely assumed that $(L_1 - M)$ is constant at all inductions and Eq. 5, becomes

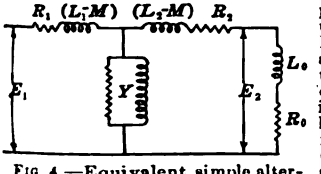


FIG. 4.—Equivalent simple alternating-current circuit for a transformer.

$$e_2 = -e_1 + R_1 i_0 + (L_1 - M)\frac{\partial i_0}{\partial t} \qquad (6)$$

19. Characteristics of a loaded transformer. The equations of a transformer supplying a load of resistance R_0 and inductance L_0 are

$$\left.\begin{aligned} R_1 i_1 + \frac{\partial}{\partial t}(L_1 i_1) + \frac{\partial}{\partial t}(M i_2) &= e_1 \\ (R_2 + R_0) i_2 + \frac{\partial}{\partial t}(L_2 + L_0) i_2 + \frac{\partial}{\partial t}(M i_1) &= 0 \end{aligned}\right\} \qquad (7)$$

From these equations the following is derived:—

$$\frac{\partial}{\partial t}\{M(i_1 + i_2)\} = e_1 - R_1 i_1 - \frac{\partial}{\partial t}\{(L_1 - M) i_1\} \qquad (8)$$

The quantities $(L_1 - M)$ and $(L_2 - M)$ are very nearly constant, but the value of M is dependent on the instantaneous value of the induction. If i_2 be taken equal to $-i_2$ to represent the load component of the primary current the transformer may be represented by the following simple alternating current diagram, Fig. 4, where Y is an admittance of such a character as to give an exciting component $(i_1 - i_2)$, which includes the core-loss current. This is known as the "Steinmetz equivalent circuit for a transformer." The current and voltage relations may be given by the vector diagram, Fig. 5, on the assumption that Y is a simple admittance.

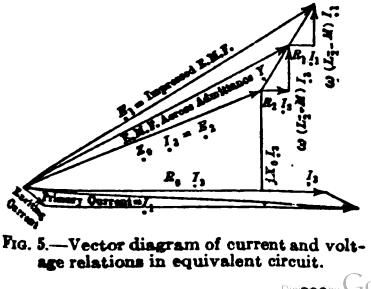


FIG. 5.—Vector diagram of current and voltage relations in equivalent circuit.

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20. The short-circuit characteristics of a transformer are obtained from those of the loaded transformer by making E_2 and L_2 equal to zero. It is usual to consider the quantity ωM in the resulting equation as infinite in which case the short-circuited transformer may be treated as a simple impedance so that the effective reactance of a transformer of unity ratio when short-circuited is the sum of $\omega(L_1 - M)$ and $\omega(L_2 - M)$. Moreover under load conditions the effective transformer impedance differs from the short-circuit value only on account of the influence of the normal induction on the permeability of the core, and since the effect of ωM may be ignored in the short-circuit reactance, the effect due the difference of ωM under short circuit and when there is normal induction in the iron being of still smaller order of magnitude may also be ignored. The quantities which in transformers under load are the equivalents of the short-circuit copper loss and impedance have been measured with varying inductions in the iron and have been invariably found to be practically constant.

21. The current in the secondary winding of a transformer supplying a load may be obtained by means of the simple alternating-current circuit shown in Fig. 4. But since the admittance Y is not readily expressible, it is inconvenient to use this circuit. Moreover the quantity $(L_1 - M)$ cannot be evaluated very exactly and therefore more or less error is introduced when it is used. The following formula derived mathematically from Eq. 6 and 7 with the assumption made in the preceding paragraph has the advantage of great simplicity

$$e_2 = R_s i_2 + L_s \frac{\partial i_2}{\partial t} + \left(R_s i_2 + L_s \frac{\partial i_2}{\partial t} \right) \tag{9}$$

where R_s and L_s are the effective resistance and effective inductance when load current is circulated in the secondary with the primary short-circuited.

22. With sine-wave secondary open-circuit voltages Eq. 9 becomes that of a simple reactive circuit having resistance equal to the sum of the load resistance and the secondary effective short-circuit resistance and having reactance equal to the sum of the load reactance and the secondary short-circuit reactance. The secondary current may then be multiplied by the ratio of transformation to obtain the primary load current, and from this the primary current is obtained by adding the equivalent sine-wave exciting current in proper phase relation. Eq. 9 under these circumstances may be represented symbolically as follows:

$$\dot{E}_2 = \{ (r_0 + r_s) + j(x_0 + x_s) \} \dot{I}_2 \tag{10}$$

where E_2 and I_2 are both vectors. The vector diagram and current loci for all loads are given in Fig. 6.

23. The construction of Fig. 6 may be explained as follows: $OA = -E_1$ or the primary impressed e.m.f., reversed in time phase. $OB = E_2$, or the secondary open-circuit e.m.f. The radius of the heavy-line circle with B as centre represents the secondary short-circuit impedance of the transformer, drawn to the same scale as OB. To obtain the loci of the secondary terminal e.m.f. for any load, bisect OB, at C_1 and draw the line C_1, C_2, C_3 at right angles. The locus of all loads having a given power-factor is a circle passing through B with its centre at some point on the line C_1, C_2, C_3. The unity-power-factor centre C_2, is obtained by making C_1, C_2 equal to C_1B multiplied by the ratio of the secondary short-circuit resistance to the secondary short-circuit reactance; the centres C_3, C_4, C_5, etc., for loads of other power-factor are obtained by making cos α_3, cos α_4, etc., equal to the respective power-factors, making the angle lag behind or lead the phase of BC_2, according as the power-factor is lagging or leading. The loci are then obtained by describing circles passing through B with these centres. The loci for different load currents are concentric circles having B as centre and radii proportional to the respective short-circuit impedance drops at these loads. Thus the secondary terminal e.m.f. with full-load secondary current and 90 per cent. leading power-factor is represented in time-phase and magnitude by the vector drawn from O to the point C where the 90 per cent. leading-power-factor circle intersects the full-load impedance-drop circle. To obtain the loci of the current vectors, describe with centre O a circle of radius to represent the effective full-load secondary current on any suitable scale; with the same centre draw another circle of radius equal to that of the

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first one multiplied by the ratio of one-half the secondary open-circuit voltage to the secondary short-circuit impedance volts at full-load current. Take OB equal in time-phase and magnitude to the secondary open-circuit voltage, draw Oe_2 at right angles to OB and make the angle e_2Oe_1 such that its cosine is equal to $\frac{\text{short-circuit reactance}}{\text{short-circuit impedance}}$; draw also a line $e_1e_2e_3$ tangential to the second circle at the point e_1; this line is the locus of the centres of the circles passing through O, which are the loci of the secondary load currents for different power-factors. e_2 is the centre for the circle passing through O which is the locus for the currents for all loads of unity-power-factor; the other centres are found in the same way as for the secondary voltage loci. The loci for different values of secondary load current are circles with O as centre and radii proportional to the effective values of the load currents. The vector for any given value of load current and power-factor of load is therefore the line drawn from O to the point of intersection of the load-current circle and the power-factor circle. The approximate primary current is then obtained by combining this vector with the vector OE representing the open-circuit exciting current.

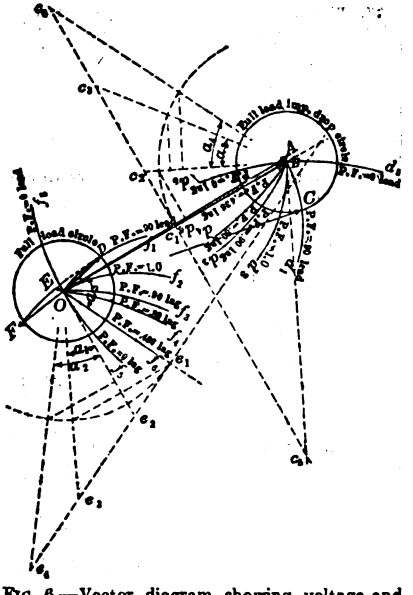


FIG. 6.—Vector diagram showing voltage and current relations in a transformer at all loads.

24. The short-circuit copper-loss with full-load current circulated in the secondary winding is not the true copper-loss, but a correction must be made on account of the I^2R loss caused by the exciting current. Part of this extra loss is practically constant at all loads and is included in the core-loss measurements; the other part varies with the load. If θ be the angle corresponding to the secondary power-factor, α the angle of hysteretic lead, I_e and I_s the effective values of the exciting current and the component of the primary current corresponding to the secondary current, respectively, then the correction to be added is

$$\text{Correction} = 2I_0I_2R_1 \sin(\theta+\alpha) \quad \text{(watts)} \qquad (11)$$

In substituting values of R_1 the effective primary resistance should be used. The correct value of induced e.m.f. at which to take the core-loss is the voltage across the admittance Y, Fig. 4, and it can be found in the usual way by Eq. 10 after $(L_1 - M)$ has been obtained. But it is not usual or necessary in practice to go to such refinements. The core-loss measured at the rated voltage plus the secondary IR drop is sufficiently close for practical work.

25. The efficiency may now be obtained by the usual formula

$$\text{Efficiency} = \frac{\text{Output}}{\text{Input}} = \frac{\text{Output}}{\text{Output} + \text{losses}} \qquad (12)$$

26. The regulation may be defined as the difference between the full-load and the no-load secondary voltage of the transformer, for the same primary

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voltage, expressed as a percentage of the full-load secondary voltage, which is also the rated voltage. If IR/E and IX/E are respectively the effective short-circuit ohmic and the reactance drops expressed as fractions of the rated voltage, then

$$\text{Regulation} = \frac{IR}{E}\cos\theta + \frac{IX}{E}\sin\theta + \frac{\left(\frac{IX}{E}\cos\theta - \frac{IR}{E}\sin\theta\right)^2}{2} \qquad (13)$$

GENERAL DESIGN

27. The design of successful commercial transformers requires the selection of a simple form of structure, so that the coils may be easy to wind and the magnetic circuit easy to build. At the same time the mean length of the windings and of the magnetic circuit must be as short as possible for a given cross-sectional area, so that the amount of material required and the losses shall be as low as possible. The form of construction should permit of the easy removal of heat by means of ventilating ducts, it should admit of being insulated in a simple and economical manner, and the windings should be of such forms as may be easily reinforced to withstand mechanical stresses.

28. Two types of transformers are in common use. When the magnetic circuit takes the form of a single ring encircled by two or more groups of primary and secondary windings distributed around the periphery of the ring, the transformer is termed a core-type transformer. When the primary and secondary windings take the form of a common ring which is encircled by two or more rings of magnetic material distributed around its periphery, the transformer is termed a shell-type transformer.

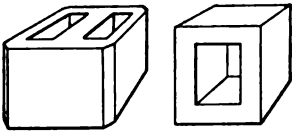


FIG. 7.—Forms of magnetic circuits of transformers.

29. The characteristic features of the **core-type** transformer are a long mean length of magnetic circuit and a **short** mean length of windings; those of the **shell-type** are short mean length of magnetic circuit and long mean length of windings. The result of these features is that for a given output and performance the core-type will have a smaller area of core and larger number of turns than the corresponding shell-type. As a general rule the core-type construction is more economical for small high-voltage transformers than the shell-type construction, the dividing line for size being dependent on the voltage. In the matter of relative weights of iron and copper, the two types tend to merge into each other if steps are taken to alter the construction so that their features are more nearly alike. Fig. 7 and Fig. 8 illustrate the forms of magnetic circuits that have been found to result in the most economical and satisfactory designs.

30. Electrical design. The fundamental formulæ in the electrical design of a transformer are those given under "General Theory," Par. 16, Eq. 4. If a certain current-density and induction be assumed, the allowable thickness of the coils for the proper cooling may be predetermined. The electrical stress between layers and between adjacent coils may also be predicted with sufficient accuracy to specify the amount of insulation that it will be necessary to use in each case.

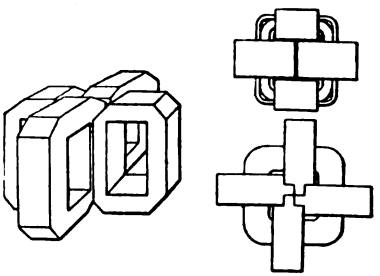


FIG. 8.—Shell-type distributed magnetic circuit.

31. The area occupied by a primary or a secondary

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conductor, including the duct space and the insulation clearances necessary to insure proper cooling and insulation respectively, and the proper mechanical allowances may be accurately calculated. Denote these two areas by a_1 and a_2 respectively and the corresponding net area of the conductors by γ_1 and γ_2. Then if P be the out-put of the transformer in watts and W_1 and W_2 the I^2R loss per lb in the primary and secondary windings at rated output and temperature θ centigrade

$$\gamma_1 = \frac{P}{E_1} \frac{0.0014\sqrt{1+0.00428\theta}}{\sqrt{W_1}} \tag{14}$$

and γ_2 may be found by substituting E_2 for E_1 and W_2 for W_1. If A_1 and A_2 be the gross areas of the magnetic circuit and the windings respectively and if S_a and S_b be the corresponding space factors the following relations are obtained

$$A_1A_2 = \frac{\sqrt{2}\,(E_1a_1+E_2a_2)\times 10^8}{\omega S_a B} \tag{15}$$

$$S_b = \frac{E_1\gamma_1+E_2\gamma_2}{E_1a_1+E_2a_2} \tag{16}$$

Where the mean length of both windings is the same W_b the mean I^2R loss per lb. will be $\sqrt{W_1W_2}$. If l_1 and l_2 are the mean lengths of one turn of each winding to be determined when the dimensions are known

$$W_b = \frac{E_1\gamma_1l_1W_1+E_2\gamma_2l_2W_2}{E_1\gamma_1l_1+E_2\gamma_2l_2} \tag{17}$$

It is in general advantageous to have $W_1 = W_2 = W_b$. Denote the ratio A_1/A_2 by X and let the ratio of the dimensions of the cross-section of the winding space and magnetic circuit be Y and Z respectively. The area and dimensions of the magnetic circuit and winding space will then be

$$A_1 = \left(\frac{A_1A_2}{X}\right)^{\frac{1}{2}}, \text{ Dimensions} = \left(\frac{A_1}{Z}\right)^{\frac{1}{2}} \text{ by } (ZA_1)^{\frac{1}{2}} \tag{18}$$

$$A_2 = (XA_1A_2)^{\frac{1}{2}}, \text{ Dimensions} = \left(\frac{A_2}{Y}\right)^{\frac{1}{2}} \text{ by } (YA_2)^{\frac{1}{2}} \tag{19}$$

The volume of iron and copper for any type of transformer may be obtained from the formulæ

$$\text{Volume of iron} = S_a(A_1A_2)^{\frac{3}{4}} f_1\left\{X, Y, Z, \frac{C_1}{(A_1A_2)^{\frac{1}{4}}}\right\} \tag{20}$$

$$\text{Volume of copper} = S_b(A_1A_2)^{\frac{3}{4}} f_2\left\{X, Y, Z, \frac{C_2}{(A_1A_2)^{\frac{1}{4}}}\right\} \tag{21}$$

where C_1 and C_2 are determined from the insulation constants and f_1 and f_2 denote that the quantities preceding it are to be multiplied by a function of the quantities in the bracket. The quantities in the brackets are not dimensional quantities and therefore f_1 and f_2 will be independent of the size of the transformer but will vary with different forms. If conditions for minimum cost and loss are introduced, Y and Z become definite functions of the remaining variables so that the functions f_1 and f_2 may be plotted in sets of curves having X as the independent variable and $C_1/\sqrt[4]{A_1A_2}$ and $C_2/\sqrt[4]{A_1A_2}$ as parameters.

32. The relations between the output of a transformer and its dimensions, weight, and cost of copper and iron, derived from the above formulæ, assuming no change in the space factors, densities and proportions, and provided that the insulation clearances between windings are very small, are approximately as follows:

Area of core	varies as	$P^{\frac{1}{2}}$	
Area of winding space	" "	$P^{\frac{1}{2}}$	
Weight	" "	$P^{\frac{3}{4}}$	
Cost	" "	$P^{\frac{3}{4}}$	.(22)
Per cent. loss	" "	$P^{\frac{1}{2}}$	
Volts per turn	" "	$P^{\frac{1}{2}}$	

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33. Core material. Silicon steel is used almost entirely for power and distributing transformers. For the first class of transformers chiefly on account of its non-ageing characteristics. For the second class on account of its extremely low hysteresis and eddy current loss. A great deal of investigation is being carried on by various manufacturers with a view of producing steels having characteristics suitable for different classes of work. A complete discussion of various classes of sheet steel for electrical apparatus will be found in Sec. 4.

34. Insulation, cooling and mechanical stresses. These factors will have a large influence on the form and dimensions of large power transformers and are taken up in detail under separate headings below.

DESIGN OF INSULATION

35. High insulation strength is one of the most important requirements of a well-designed transformer. However, provided that the proper strength is obtained at every point, the less insulating material used the better, because the insulating material is the chief factor limiting the temperature at which it is permissible to operate and it is also the main factor in producing the rise of temperature of the windings.

36. The electric stresses to which a transformer is subjected in service may be transient in nature, or they may be steady. Belonging to the former class are surges set up by switching, breaking down of line insulators, arcing grounds, and short-circuits. Steady electric stresses are caused by such accidents as the grounding of one line of a transmission circuit, and will be preceded by a surge or transient wave due to the change in the electric field brought about by the new condition of stress. Thus high electric stress to ground, in a transformer, may be preceded by high stresses between coils and turns of the high-potential parts of the windings. A breakdown between turns in a high-voltage transformer may therefore be due to a combination of the two forms of stress. Another form of stress that may cause breakdown of the low-tension winding is likely to occur when the electrostatic capacity between the high-tension and low-tension windings is high in comparison with that of the low-tension winding to ground, in which case a dissymmetry of the high-tension circuit such as that due to a ground on one line may cause a potential elevation of the low-tension winding sufficient to break down the insulation, or to cause loss of life.

37. The transient stresses are difficult to estimate with any degree of certainty and the designer usually has to satisfy himself with results obtained by experience with transformers in service.

38. The steady stresses may be easily calculated, and the usual practice is to design the insulation so that it will withstand a difference of potential between the low-tension and high-tension windings and between case and high-tension winding, ranging from two to two and one-half times the possible steady stress under service conditions.

39. The insulation between adjacent coils and adjacent turns of the transformer must be capable of withstanding with an ample margin of safety the normal and transient stresses that occur. It is customary in large transformers to give an overpotential test of double voltage, mainly for the purpose of making sure that there are no weak spots in the coil insulation.

40. Effect of polarity of windings. Polarity in a transformer depends upon the relative direction of the induced electromotive forces in the primary and secondary windings considered with respect to the two adjacent ends of the two windings.* In a single-phase transformer under normal conditions of service, the middle points of both primary and secondary windings are at ground potential; but the maximum difference between adjacent primary and secondary coils may be half the sum of the primary and secondary voltages or half their differences according to the polarity. This factor becomes of extreme importance in the design of transformer for interlinking two high voltage systems.

* A full discussion of this question will be found in an article by C. Fortescue, Electric Journal, 1907, and also one by Wm. McConahey, Electric Journal, 1910.

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41. Methods of insulating. The methods employed in insulating a transformer will depend largely upon the type, upon the high-tension voltage, and upon the method of cooling, employed. Small transformers to operate on 2,200-volt circuits are usually insulated between the high-tension and low-tension windings with a cylindrical barrier of mica and fibrous material about $\frac{1}{32}$ in. thick. The usual way of applying this barrier is to wrap it over one winding; the second winding is then wound on top of it. One company uses a tube of mica with a pure shellac bond which has been moulded from a circular cylinder under heat to the proper form with which to insulate the high-tension and low-tension windings from each other. The adjacent ends of the two windings are insulated from each other by means of collars or spacing pieces and heavy paper corner pieces. The complete coil may be vacuum dried and impregnated with a compound insoluble in oil, before the iron is built in, or the iron may be built in first and the whole transformer impregnated.

42. Insulation between turns and layers. In small transformers in which round wire is used, and where the volts per turn are small, and the windings are not subjected to high stresses, the cotton covering is sufficient for insulation between turns, and with proper subdivision of the coils only a little additional insulation need be used between layers. In larger transformers where round wires are used, the layers must be heavily insulated. In high-voltage transformers the line coils are sometimes wound with cord between adjacent turns to secure high insulation strength. In large transformers where the conductors are copper straps, the coils are wound spirally with the conductor flat, and the conductor is either heavily sleeved with cambric or cloth, or, according to the practice of one company, the adjacent turns are insulated from each other by micanite strips. The turns of the coils next to the line are always heavily reinforced. In wire-wound coils the voltage per layer rarely exceeds 150 volts in the inner coils and is much less than this in the coils nearest the line.

43. Coil insulation. In order to reduce the stress and thereby obtain more effective insulation, the windings are subdivided into coils. The adjacent coils may be insulated from each other by taping, or by insulating washer and edge strips or angle pieces. For insulating the coils of small transformers and air-blast transformers the former method is used by some manufacturers, the coils first being impregnated with an oil-proof gum. For insulating the coils of large oil-insulated transformers the oil spaces between ducts and one or more $\frac{1}{4}$-in. fuller-board washers are depended on.

44. The insulation between the high-voltage and low-voltage windings in large transformers of the shell-type is constructed of sheets of fuller-board about $\frac{1}{4}$ in. thick and angle pieces of the same material. The sheets of fuller board and the angle pieces are arranged in the form of a boxing surrounding each group of high-tension or low-tension coils; all joints are lapped and in high-voltage transformers the corners of the coils are insulated by specially formed angle pieces so that when the insulation of a group of coils is completed, it forms a boxing around the group which completely isolates it from the adjacent group.

45. Heavy cylindrical tubes of paper are used between the high-voltage and the low-voltage windings in large **core-type** transformers. One company uses a paper tube rolled with shellac as a bond; another company uses fibre or fuller-board tubes. **Small high-voltage core-type transformers** may have their high-voltage winding wound directly on one of these tubes; this furnishes a cheap and effective method of manufacture.

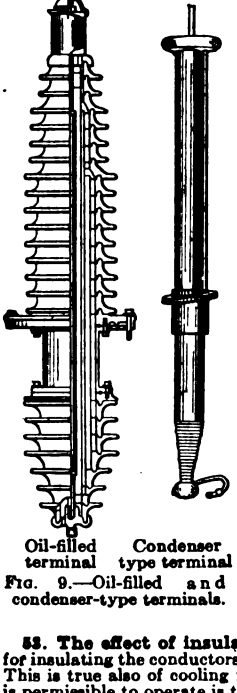
46. The insulating value of the oil, in oil-insulated transformers, is depended on very largely to help insulate the transformer; this is done by interspersing the oil and the fuller-board in all the barriers. At the ends of the high-tension coils the insulation is effected mainly by oil spaces reinforced with corner pieces of fibrous material.

47. In air-blast transformers the same general method of construction is used, but in addition the coils are heavily taped and treated with waterproof compounds. In air-blast transformers the insulation clearances are very much larger than in oil-insulated transformers, particularly at the ends of the coils where distance insulation must be used to a great extent.

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48. Outlet terminals. The outlet terminals in general use are the condenser terminal (Par. 49) and the oil-filled terminal (Par. 50).

49. The condenser-type terminal consists (Fig. 9) of alternate cylinders of thin tin-foil and shellac-treated paper, rolled hot on a central brass rod of the proper diameter: they are so arranged that the capacities between adjacent tin-foil cylinders are the same throughout, and the tin-foil cylinders differ in length by equal steps. The potential stress is distributed evenly over the whole length of the terminal. The addition of a disc at the top of the terminal and an external cylinder of insulating material extending between the flange and the disc, the space between the condensers and the cylinder being filled with gum, complete the outlet lead.



Oil-filled terminal — Condenser type terminal

FIG. 9.—Oil-filled and condenser-type terminals.

50. The oil-insulated terminal (Fig. 9) depends upon oil as an insulator and as a means for insuring equal distribution of heat in the terminal. It consists of segments of porcelain or moulded material cemented together to form an enclosure for the oil; a conducting rod extends from top to bottom of this enclosure. The oil space is subdivided by insulating cylinders to prevent lining up of particles in the oil.

51. In transformers for high-voltage transmission the coils adjacent to the line terminals are more heavily insulated from one another than the rest of the coils. In large transformers the normal stress between adjacent coils is seldom permitted to exceed 15,000 volts. As the size of a transformer is increased, keeping the current density and the coil thickness the same the voltage per coil will vary inversely as the fourth power of the output. Since the thickness of the coils and the spacing between them are usually determined by the cooling requirements, a large transformer is more easily insulated than a small one.

52. Grounding of the neutral point. A considerable saving in cost of insulation may be obtained if transformers are designed for operation with the neutral point of the line-circuit grounded. The insulation stresses to which a transformer may be subjected in service are thereby greatly reduced and the danger of breakdown of low-tension insulation due to the effect described in the latter part of Par. 36 is entirely eliminated, in polyphase transformations.

53. The effect of insulation on cooling. The fabrics which are used for insulating the conductors deteriorate when subjected to high temperature. This is true also of cooling fluids such as oil. The temperature at which it is permissible to operate is therefore limited by these factors. These limitations are particularly emphasized in small transformers and those of the air-blast type where the heat must pass through thick barriers.

COOLING SYSTEMS

54. Methods of removing heat. The losses in a transformer appear as heat in the windings and the core. Means must therefore be provided for removing it; otherwise high temperature will result, which will destroy the fibrous materials used for insulating the various parts of the transformer. Methods of removing heat may be classified as follows:

(a) **By natural convection of air and radiation.** This method is employed in certain special cases for small distributing transformers up to

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25 kv-a. It is the method generally used for cooling instrument and small switchboard transformers.

(b) **By forced convection of air.** Transformers in which this method is used are commonly called **air-blast transformers.** They may be built with ratings as large as required and voltages not exceeding 35,000 volts.

(c) **By natural convection and radiation with two fluids.** Oil-insulated air-cooled transformers are cooled in this manner. This method may be applied to transformers for all voltages and for ratings up to 8,000 kv-a.

(d) **By a combination of natural convection of a fluid medium with forced convection of cooling air.** This method has not been used in this country to any great extent, but is in great favor in Europe.

(e) **By natural convection of an insulating fluid which is cooled artificially by another fluid.** This method is used in oil-insulated water-cooled transformers.

(f) **By forced convection of an insulating fluid which may be cooled in any convenient way.** This method has been employed to cool large transformers by forcing the cooled fluid through the windings.

Forced oil circulation with the oil cooled by air-blast may be employed in one self-contained unit.

56. Conduction outward to the surface exposed to the cooling medium is the first step in the removal of heat from the winding of a transformer. This conduction will partly be through copper and partly through insulation. The flow of heat between parallel faces of any material for a difference of temperature of 1 deg. cent. may be given in watts per sq. in., and in this work it is convenient to express it in this form. The **temperature gradient** at any point of the coil will therefore be opposite in direction and proportional to the maximum value of the heat flux (expressed in watts per sq. in.) at that point.

57. The maximum temperature rise through a coil at any point will be the line integral of the temperature gradient in the direction of the heat flow to that point.

58. The average temperature rise through a coil at any point of its surface is the weighted average temperature rise of all the portions of the conductors contributing to the heat flow at that point.

59. Cooling by convection is the next step in the removal of heat conducted to the surface of the coil. Convection currents are caused by the upward motion of the heated fluid, thereby permitting unheated fluid to displace it. Therefore, it is essential in order to obtain efficient cooling of the coil surface, that the windings be so constructed that they present vertical surfaces, forming paths free from obstructions to the flow of these convection currents. After the heated fluid has risen to the surface it must be cooled, and in order that this may be done efficiently its temperature must be as high as compatible with the limiting value set for the maximum temperature of the transformer. The winding must therefore be so constructed that no part of the fluid flowing past a surface shall be far removed from it; furthermore, the difference in velocity between the fluid in intimate contact with the surfaces of the winding and that furthest removed must be kept as small as possible.

60. The structural requirements are fulfilled by arranging the windings so that the exposed surfaces are concentric cylinders with vertical axes or parallel vertical planes. The thickness of the coils is determined by the current-density in the copper and the permissible maximum temperature-rise through the coil.

60. The physical characteristics requisite in a cooling fluid in order that it shall be an efficient cooling agent for transformers are:

(a) It must be a good insulator.
(b) It must have good thermal conductivity.
(c) It must have high specific heat.
(d) It must have a high coefficient of expansion.
(e) Its viscosity must be as low as possible.
(f) It must be capable of withstanding the operating temperatures without carbonizing or producing gummy deposits on the coil surfaces.
(g) It must be stable, difficult to ignite, and free from acids or any other ingredient that will attack fibrous materials, iron, copper, or varnishes.

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The reason for most of these requirements are obvious, but (b), (c), (d) and (e) require some explanation, which is given in the next paragraph.

61. Explanation of heat transfers in cooling fluid. Consider two adjacent surfaces of a winding taking the form of two parallel planes a small distance apart, and assume that all the heat is emitted in a direction normal to the planes. The fluid directly in contact with the surface will first become heated and expand, thereby becoming lighter and rising. It will thus at every point of its passage assume a temperature which will increase progressively along the vertical. At the lowest point of the coils the oil nearest the surface will perform all the cooling, but as it rises the temperature gradient through the fluid normal to the surface will increase, thus permitting the conduction of heat to the fluid further removed from the surface. The temperature gradient through the oil at the top of the coils will therefore depend upon the velocity of the fluid and its distance from the surface. The more nearly uniform the velocity of the fluid at each point, the less will be the temperature gradient. The velocity of the fluid at each point depends among other things upon the viscosity of the fluid being more uniform the lower the viscosity. High specific heat is important because it permits a given amount of heat to be removed per unit time at lower velocity and lower temperature rise along the surface. High thermal conductivity is necessary so that heat may be transmitted through the fluid normal to the surface with a small temperature gradient. It should be noted that where the fluid is a gas, a certain amount of work is absorbed during expansion, so that the specific heat at constant pressure should be used.

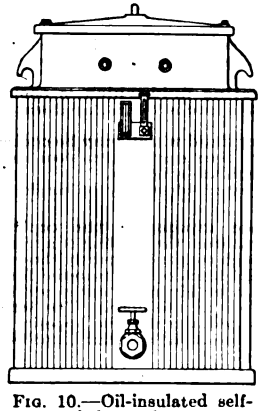


FIG. 10.—Oil-insulated self-cooled transformer.

62. The temperature difference between the fluid at the top of the coil and that at the bottom is a measure of the force required to circulate the fluid. Part of this force is used up in overcoming the friction offered by the surfaces and the viscosity of the fluid.

63. In transformers cooled by free convection in air the remainder of this force is that necessary to bring the velocity of the air up to the required value to effectively remove the losses. In **oil-insulated self-cooled types** (Fig. 10), where the transformer is immersed in a liquid which circulates by free convection, cooling the surfaces of the windings and being cooled in turn at the surface of the container by convection of the air, the hydraulic force or head developed in the windings due to the difference in temperature has to overcome not only the resistance to flow within the windings themselves, but also that external to the windings due to the sides of the case. In addition to this there is a back pressure or counter-head which represents the force required to overcome the friction resistance of the external surface of the case to the convection currents of air and that required to set them in motion.

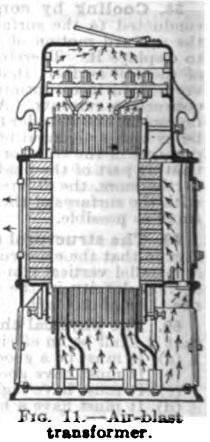


FIG. 11.—Air-blast transformer.

64. In the air-blast method of cooling (Fig. 11), instead of depending solely on free convection of air to cool the transformer, pressure is used and air is forced through the windings. The temperature rise of the hottest part of the surfaces, above

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the incoming air, may therefore be made as small as desired by using sufficient pressure, and the limits of this method of cooling will be set only by the cost of maintaining a large flow of air at sufficient pressure, and by the temperature gradient through the coils and insulation.

65. Artificial cooling of the hot oil after it flows from the top of the coils affords the same advantage in oil-immersed transformers (Par. 64). In water-cooled transformers (Fig. 12) this is done by placing a coil of pipe near the surface of the oil, through which cold water is circulated.

66. In forced oil circulation (Fig. 13), the liquid is circulated as well as cooled artificially, and a still further gain can be made in efficiency of cooling, but it is only in transformers of large capacity that the gain in cooling efficiency overbalances the increased outlay.

67. Limitations in design on account of cooling. As the size of the transformer is increased, keeping constant the current density, the

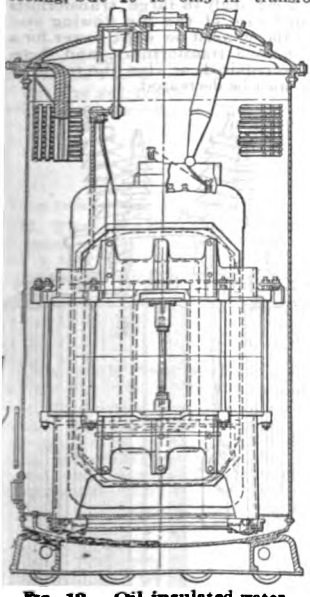


FIG. 12.—Oil-insulated water-cooled transformer.

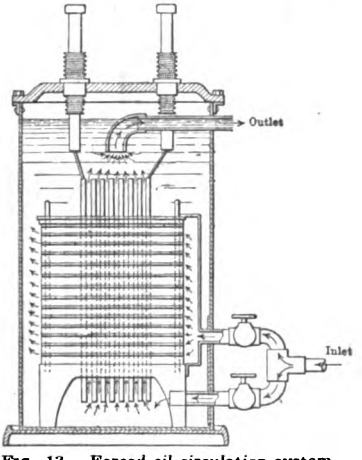


FIG. 13.—Forced-oil circulation system of cooling.

induction and the watts lost per sq. in. of effective coil surface, the dimensions will be proportional to the one-fourth power of the output. The duct area per watt lost will therefore become less, and the length of path the cooling fluid must travel will be greater.

68. In transformers cooled by natural convection a larger difference in temperature will be required between the top and the bottom of the coils to set up the necessary circulation of air, the greater the capacity of the transformer, on account of the decrease of the duct area per watt lost and the increase of the mean length of flow path, with increasing capacity or rating. Consequently, unless these factors are changed in proportional ratio with the losses, the temperature rise of this style of transformer will increase as the size increases.

69. In oil-insulated self-cooled transformers as the capacity or rating is increased there is more resistance to the flow of oil in the ducts on account of their greater length. Moreover since the dimensions of the case are determined largely by the dimensions of the coils and these are

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approximately proportional to the one-fourth power of the output while the losses increase as its three-fourth power, the additional surface necessary to dissipate the heat must be obtained by corrugating the tank surface. The air flow has therefore to encounter a more constricted area of entry and a longer path of higher resistance. The volume of air per watt lost will consequently decrease and the average temperature of the air flowing over the surface increase, resulting in a higher average temperature of the oil, unless the gradient between the oil and cooling air has been sufficiently decreased by increasing the tank area per watt lost. The maximum temperature of the oil will tend to be higher, and therefore the maximum temperature of the windings which is the limiting factor in any electrical apparatus will also tend to be higher. Accordingly in large transformers the difference between the average temperature of the air flowing over the surface and the average temperature of the oil must be kept lower for a given temperature rise in the coils than in small transformers, and therefore a larger tank area per watt lost, will be required, or else the temperature gradient through the coils themselves must be decreased.



FIG. 14.—Oil-insulated self-cooled transformer (tubular type).

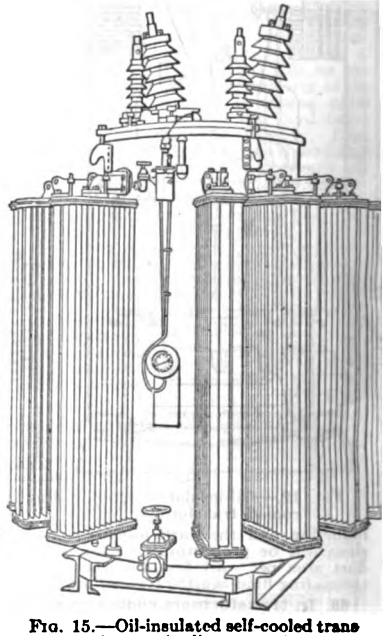


FIG. 15.—Oil-insulated self-cooled transformer (radiator type).

70. Tubular and radiator type tanks. The usual course is a compromise between these two methods of keeping down the temperature rise in the coils, but with very large transformers this becomes costly and more efficient cooling tanks must be used, good examples of which are the tubular and radiator types of tanks (Figs. 14 and 15) or else recourse must be had to artificial methods of cooling such as water cooling, forced circulation, etc.

71. The watts lost per sq. in. of coil surface for cylindrical coils of large radius and for discoidal coils, may be obtained by very simple formu-

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las from the current-density or the loss in watts per lb. at operating temperature.

W_s = watts loss per sq. in. of coil surface at θ deg. cent.,
W_b = watts loss per lb. of copper at θ deg. cent.,
γ = area of bare conductor in sq. in.,
b_0 = thickness or diameter of wire uninsulated,
b_1 = thickness or diameter of insulated wire plus layer insulation,
n = number of turns per layer in layer-wound coil or number of layers in cylindrical coil,
d_0 = width of rectangular conductor uninsulated.

$$\left.\begin{aligned} b_0 d_0 &= \gamma + c \text{ (for rectangular wire)} \\ b_0^2 &= \frac{4}{\pi}\gamma \text{ (for round wire)} \end{aligned}\right\} \quad (23)$$

where c is the difference in area between a circle having a diameter equal to double the radius of the corners of the conductor and its inscribed square.

72. The values of W_s (Par. 71) for different types of layer-wound coils with one surface exposed are

$$\left.\begin{aligned} W_s &= \frac{0.3212 n b_0 d_0}{b_1} W_b \quad \text{(rectangular wire)} \\ W_s &= \frac{0.252\, n b_0^2}{b_1} W_b \quad \text{(round wire)} \end{aligned}\right\} \quad (24)$$

When two sides are exposed the results given above are divided by two.

73. The temperature gradient through a coil having one surface exposed may be obtained on the assumption that it is homogeneous, has a thermal conductivity λ_0 and thickness δ_0 and that the insulation covering has thermal conductivity λ_1 and thickness δ_1. In which case

$$\left.\begin{aligned} \theta_{max} &= W_s\left(\frac{\delta_0}{2\lambda_0} + \frac{\delta_1}{\lambda_1}\right) \quad \text{deg. cent.} \\ \theta_{mean} &= W_s\left(\frac{\delta_0}{3\lambda_0} + \frac{\delta_1}{\lambda_1}\right) \quad \text{deg. cent.} \end{aligned}\right\} \quad (25)$$

Coils with two surfaces exposed are considered as two coils of one-half the thickness with one surface only exposed.

74. The equation of cooling for an oil-insulated self-cooled transformer may be based on the assumption that the emissivity of the case is a constant. The calculation is made in two steps: first, the calculation of the mean temperature reached by the oil above the mean air temperature; second, the calculation of the mean rise of the windings above the mean oil temperature. Let

P_0 = total loss = $P_1 + P_2$, = iron loss + copper loss,
α_0 = emissivity of tank in watts per sq. in. per deg.,
α_s = emissivity of coil surface in watts per sq. in. per deg.,
A_0 = area of cooling surface of tank in sq. in.,
A_s = area of cooling surface of coils in. sq. in.,
s_0 = specific heat of oil,
s_s = specific heat of coils,
θ_0 = initial temp. rise (cent.) of oil above air,
θ_1 = rise of oil temp. (cent.) after time t_1,
θ_s = initial rise (cent.) of coils above oil,
θ_2 = rise of coil temp. (cent.) after time t_1 (hours),
G_0 = weight of oil (pounds),
G_1 = weight of coils (pounds),
t_1 = time measured in hours to raise temp. of oil from θ_0 to θ_1

$$\theta_1 = \frac{P_0}{\alpha_0 A_0} - \frac{\left(\frac{P_0}{\alpha_0 A_0}\right) - \theta_0}{10^{\left(\frac{0.823\,\alpha_0 A_0 t_1}{G_0 s_0}\right)}} \quad \text{(deg. cent.)} \quad (26)$$

$$t_1 = 1.215\left(\frac{G_0 s_0}{\alpha_0 A_0}\right) \log_{10} \frac{\left(\frac{P_0}{\alpha_0 A_0} - \theta_0\right)}{\left(\frac{P_0}{\alpha_0 A_0} - \theta_1\right)} \quad \text{(hours)} \quad (27)$$

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The same equations apply to θ_a, and θ_b if we substitute these values for θ_0 and θ_1 respectively; and also substitute P, A_s, σ_s, G, and α_s for $P_0 A_0$, σ_0, G_0, and α_0 respectively; we shall then have the temperature rise of the coils above the oil at the end of an interval t_1, starting with a temperature rise θ_0.

75. In water-cooled transformers the length of cooling coil required will depend upon the rate of flow of the water. Using the same symbols as before, except that the temperature rises will be measured above the incoming water, we shall have, if radiation from the surface of the tank is negligible and taking θ_w as the temperature rise of the water, F as the flow in gallons per min., L as the length of cooling coil in feet and α_w the emissivity of the surface of the cooling coil in watts per ft. per deg. cent.,

$$\theta_w = \frac{0.0038 P_0}{F} \tag{28}$$

$$L = 606 \frac{F}{\alpha_w} \log_{10} \frac{\theta_0}{\theta_0 - \theta_w} \quad \text{(feet)} \tag{29}$$

Temperature rise above entering water under steady conditions

$$= \frac{0.0038 P_0}{F\left[1 - \frac{1}{10^{\left(\frac{0.00165 \alpha_w L}{F}\right)}}\right]} \quad \text{(deg. cent.)} \tag{30}$$

Denote the bracketed portion of the denominator of the above fraction by C; then,

$$\theta_1 = \frac{\theta_w}{C} - \frac{\frac{\theta_w}{C} - \theta_0}{10^{\left(\frac{2165 F C t_1}{G_0 \sigma_0}\right)}} \quad \text{(deg. cent.)} \tag{31}$$

$$t = \frac{G_0 \sigma_0}{2165 F C} \log_{10} \frac{\frac{\theta_w}{C} - \theta_0}{\frac{\theta_w}{C} - \theta_1} \quad \text{(hours)} \tag{32}$$

C is constant for a given length of pipe and flow of water. The temperature rise of the coils above the oil may be obtained by the formulas given in the last paragraph. The above formulas with some modification may be used for forced circulation.

76. The cooling surface required for a transformer having a rise of 40 deg. cent., based on a room temperature of 25 deg., will vary from 4 sq. in. per watt lost, to 8 or 9 sq. in., according to the size of the transformer. The value of α_0 will vary from 0.008 to 0.004 watts per sq. in. per deg. cent.

77. The following relations will be found useful to transformer designers. Energy dissipated in 1 lb. of copper at the rate of 1 watt will raise the temperature of the copper at the rate of ½ deg. cent. per min. if no heat be permitted to escape. Water flowing at the rate of 3.8 gal. per min. will absorb 1,000 watts, with a temperature rise of 1 deg. cent. Air, at atmospheric pressure, flowing at the rate of 1,650 cu. ft. per min. will absorb 1,000 watts, with a temperature rise of 1 deg. cent.

MECHANICAL DESIGN AND COIL GROUPING

78. Mechanical stresses in service are due to the heavy currents developed in electrical apparatus under short-circuit, caused by the tremendous amount of energy developed in modern electrical systems. Reactance in a transformer, on account of the great length of the leakage paths in air, furnishes practically the same protection to connected apparatus as an air reactance.

79. Coil grouping and reactance. The reactance of a transformer depends on the grouping of the high-tension and the low-tension windings. The same general principles apply to the grouping of the windings of any type of transformer. The element of a given grouping is formed by a set of high-tension and low-tension coils of equivalent number of turns, generally an even submultiple of the total number of turns, placed as near together as

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the insulation will permit. This is termed a group and is designated thus: *HL* or *LH*. A grouping arranged thus, *LHHL*, is a symmetrical 2*HL* grouping; a group arranged thus, *LHHLLHHL*, is a symmetrical 4*HL* grouping, and so on. Given a stated number of turns, and a thickness of insulation between high-tension and low-tension windings very thin compared with the coil spaces, the reactance varies approximately as the reciprocal of the square of the grouping. A convenient method of calculating reactance is to consider both the high-tension and the low-tension coils in a given element as each concentrated into a thin shell one-third of the combined thickness of the coils from the surface next to the insulating barrier between the high-tension and low-tension coils.

80. Influence of mechanical stress on design of winding. High reactance may be obtained in three ways: (a) By reducing the grouping; (b) by increasing the number of turns; (c) by increasing the spacing between coils. The methods (a) and (b) increase the mechanical stress for a given value of current, while the method (c) decreases it, but the latter is costly; a compromise between these methods is best. All of the coil groups are subjected to compressive forces during short-circuit, and must therefore be properly supported. In shell type transformers, to prevent buckling of the coils under short-circuit, one company uses two heavy T-beams, spread apart by two end-studs equipped with threads and nuts for the purpose. The free ends of the coils in all types of large transformers should be held firmly in position by bracing against the end-frames or by clamping the coils together between heavy plates by tiebolts.

81. Formulas for reactance. The reactance in ohms is equal to ωL, where L is given in henrys. The value of L may be obtained by the following formulas:

Shell-type discoidal coils (Fig. 16);

$$L = \frac{10.6n^2(l_1 + l_2)(2Nc+b)}{N^2(a_1+a_2)\times 10^9} \text{ (henries)} \quad (33)$$

Shell-type cylindrical coils (Fig. 17);

$$L = \frac{10.6n^2l(2Nc+a)}{N^2b\times 10^9} \text{ (henries)} \quad (34)$$

Core-type rectangular-core concentric coils (Fig. 18);

$$L = \frac{10.6n^2(l_1 + l_2)(2Nc+a-d)}{N^2(b_1+b_2)\times 10^9} \text{ (henries)} \quad (35)$$

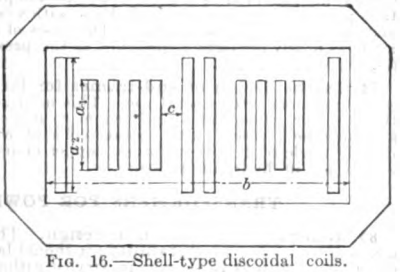


FIG. 16.—Shell-type discoidal coils.

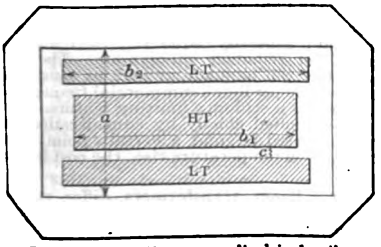


FIG. 17.—Shell-type cylindrical coils.

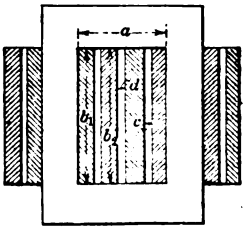


FIG. 18.—Core-type rectangular core concentric coils.

Where n is the number of turns in the winding, l_1 l_2 are the primary and secondary mean length of winding, l is the mean length of complete winding,

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N is the number of HL groups, c is the space between adjacent high-tension and low-tension windings, and a_1, a_2, b_1, b_2, b and d are as shown in Figs. 16 to 18.

82. Formulas for mechanical force exerted on coils. In a transformer the electrokinetic energy is given by

$$W = \frac{1}{2} L I_1^2 \qquad \text{(Joules)} \qquad (36)$$

where I_1 is the primary current, and therefore since $F = \frac{\partial w}{\partial x}$

$$F = \frac{1}{2} I_1^2 \frac{\partial L}{\partial x} \times 10^7 \qquad \text{(dynes)} \qquad (37)$$

x being in the direction of the maximum force, that is, at right angles to the surface of the coils. For shell-type transformers with discoidal coils,

$$F = \frac{1}{2} I^2 \left[\frac{4\pi n^2 (l_1 + l_2)}{4.45 \times 10^7 N^2 (a_1 + a_2)} \right] \qquad \text{(lb.)} \qquad (38)$$

83. Mechanical design of cases. Where fluted cases are used they should be made of ingot steel at least 0.079 in. thick, except for transformers below 100 kw., then $\frac{1}{16}$ in. may be used. Cases for oil-insulated self-cooled transformers have the sides cast in a base of cast iron. Boiler-iron cases such as are used for water-cooled transformers are usually guaranteed to withstand a pressure of 50 lb. per sq. in. The covers of large transformers are provided with vents to release the pressure if an explosion should take place. The tank is provided also with a large gate valve, so that the oil may be drawn off very quickly. The cases of large transformers should be made as nearly air-tight as possible, as this prevents dirt or moisture finding its way into the tank.

84. In the design of end-frames for large transformers structural steel has come into general use. This affords a much greater latitude to the designer, as he then has freedom to make the proportions of the core anything he pleases. The cooling coils of water-cooled transformers are usually made of $\frac{1}{2}$- to 1-in. brass, copper or iron pipe and are tested up to 250 lb. per in. hydraulic pressure.

TRANSFORMERS FOR POWER SERVICE

85. General consideration in design. The most important quality in a power transformer is **durability**; it should be able to withstand the most exacting conditions to be met in service without being sensibly weakened. It is important that the insulating material shall not be subjected to excessive temperatures, and therefore every portion of the coil surfaces should be well exposed to the cooling medium. The coils directly connected to the lines in high-voltage transformers should have reinforced insulation.

86. The cheapest transformer consistent with durability that has a reasonably good performance, is what is generally required. Such features as efficiency and regulation are usually of secondary importance. The flux-density in the iron of such a transformer will be made as high as consistent with a reasonable exciting current; the loss per lb. at commercial frequencies in silicon steels is so low that the core-loss is seldom a limiting feature. The current-density, on the other hand, is limited chiefly by considerations of cost, because when the density is increased beyond a certain point, for a transformer designed to operate at a given temperature rise, the cost begins to increase again.

87. Types and characteristics. Power transformers differ mainly in the methods used to cool them: the characteristics pertaining to different methods of cooling are taken up under "Cooling" (Par. 54 to Par. 77). Transformers cooled by natural circulation of oil and air must be designed on a more liberal scale than water-cooled transformers, or those cooled by forced oil circulation, and therefore the losses will be lower in the former than in the latter. Air-blast transformers, on account of the heavy insulation and large insulation clearances needed, are not as efficient as other power transformers of the same voltage-class.

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88. Large transformers for general power service are usually built in one of the following types: self-cooled in tubular or radiator tanks; water-cooled; oil-insulated with forced circulation of air; forced-oil-circulation type; or air-blast. Their characteristics are moderate efficiencies, low temperature rise, and durability. They may be either of the shell-type or the core-type of construction, according to size and voltage; if of the latter type, cruciform cores and circular coils are used.

89. Three-phase transformers. Two types are in general use, viz., the **core-type** and the **shell-type.** The core-type is illustrated in Fig. 19. It consists of a magnetic circuit having three "legs," each of which carries the flux due to the winding of one phase; since these fluxes flow toward a common point the third harmonic must be practically absent. It is possible, therefore, to use a star-star connection with this type of transformer without producing voltage distortion. The shell-type three-phase transformer does not differ materially from three single-phase transformers; Fig. 20 illustrates such a type of transformer. It will be noted that a small amount of iron is saved, but though the total saving in material over three single-phase transformers is small, there is a decided gain in cost of installation of one three-phase transformer over three single-phase transformers, and it occupies considerably less floor space. The performance of three-phase, shell-type transformers may be obtained with reasonable accuracy by taking the values for single-phase transformers of one-third the rating, the water rates and weights being multiplied by three. For the core type three-phase take a single phase of two-thirds the rating and add 50 per cent. to the water rate and weight.

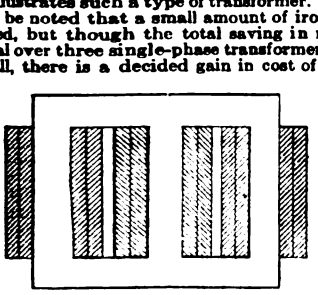


FIG. 19.—Core-type three-phase transformer.

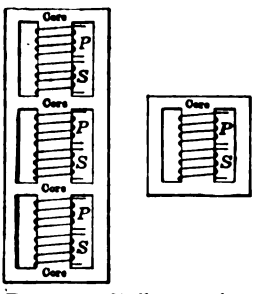


FIG. 20.—Shell-type three-phase transformer; shell-type single-phase transformer of one-third rating shown for comparison.

90. Transformers designed for outdoor service. There is a large and increasing demand for these transformers in large voltage transmission systems owing to the cost of buildings and wiring increasing very rapidly as the transmission voltage increases.

91. The design of the outlet terminal for outdoor service is not very different from the design of an indoor bushing except that, on account of the rain test it must needs stand, it is usually longer and in the condenser type the terminal proper is encased in a sheath of porcelain petticoats or bells nesting into each other and sealed with a cement. The space between the terminal and the porcelain sheath is filled with a gum of high specific inductive capacity and high melting-point.

92. Voltage classification. Standard transformers are classified according to the voltage of the transmission lines on which they are intended to operate. The voltages which are considered standard are as follows:

2,200	22,000	110,000
6,600	33,000	132,000
11,000	44,000	154,000
13,200	66,000	220,000
16,500	88,000	

Step-down transformers designed for these voltages are usually provided

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with taps giving four steps of 2.5 per cent. each. Step-up transformers provided with taps are considered as special. The usual secondary distributing voltages are considered standard. Transformers used for interconnecting two high-voltage systems are considered special.

93. A standard transformer is completely specified when the method of cooling, the frequency of the circuit (either 25 or 60 cycles), the voltage class, and low-tension voltages are given. Manufacturers have type numbers or letters for their standard lines, and in some cases two different lines may overlap for a few sizes. In general, however, no ambiguity will exist if the method of cooling is specified with the other data required.

94. Tables giving ratings, efficiencies, regulation and weights typical of standard single-phase oil-insulated air-cooled transformers. These transformers have a guaranteed temperature rise not exceeding 55 deg. cent. at continuous full-load rating. They are maximum rated according to the A. I. E. E. standardisation rules, and the insulation tests are in accordance with these rules (see also Electric Power Club Standardization Rules). The tables follow in Par. 95 to Par. 102.

95. Single-phase—60 Cycles—11,000-volt Class

Kv-a.	Efficiencies			Regulation		Net weight including oil
	½ load	¾ load	Full load	100% p. f.	80% p. f.	
250	97.3	97.7	97.8	1.5	4.0	5,600 lb.
333	97.5	97.8	97.9	1.4	4.0	6,400 lb.
400	97.7	98.0	98.0	1.3	3.9	7,900 lb.
500	97.8	98.1	98.1	1.3	3.9	9,000 lb.
667	97.9	98.2	98.2	1.2	3.9	9,500 lb.
833	98.0	98.2	98.3	1.1	3.8	12,000 lb.
1,000	98.1	98.3	98.4	1.1	3.8	16,000 lb.

96. Single-phase—60 Cycles—22,000-volt Class

Kv-a.	Efficiencies			Regulation		Net weight including oil
	½ load	¾ load	Full load	100% p. f.	80% p. f.	
250	97.2	97.6	97.7	1.6	4.3	5,800 lb.
333	97.4	97.7	97.8	1.5	4.2	6,700 lb.
400	97.6	98.9	97.9	1.5	4.2	8,200 lb.
500	97.7	98.9	98.0	1.4	4.1	9,300 lb.
667	97.8	98.0	98.1	1.4	4.1	12,000 lb.
833	97.9	98.1	98.2	1.3	4.0	15,000 lb.
1,000	98.0	98.2	98.3	1.2	4.0	17,000 lb.

97. Single-phase—60 Cycles—33,000-volt Class

Kv-a.	Efficiencies			Regulation		Net weight including oil
	½ load	¾ load	Full load	100% p. f.	80% p. f.	
250	97.1	97.5	97.6	1.6	4.8	6,000 lb.
333	97.3	97.6	97.7	1.5	4.7	8,000 lb.
400	97.5	97.8	97.8	1.5	4.7	9,000 lb.
500	97.6	97.9	97.9	1.4	4.6	9,600 lb.
667	97.7	97.9	98.0	1.4	4.6	14,000 lb.
833	97.8	98.0	98.1	1.3	4.5	16,000 lb.
1,000	97.9	98.1	98.2	1.3	4.5	18,000 lb.

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98. Single-phase—60 Cycles—44,000-volt Class

Kv-a.	Efficiencies			Regulation		Net weight including oil
	½ load	¾ load	Full load	100% p. f.	80% p. f.	
250	97.0	97.4	97.5	1.7	5.6	6,400 lb.
333	97.2	97.5	97.6	1.6	5.5	8,200 lb.
400	97.4	97.7	97.7	1.6	5.4	9,300 lb.
500	97.5	97.8	97.8	1.5	5.4	9,800 lb.
667	97.6	97.8	97.9	1.5	5.3	16,000 lb.
833	97.7	97.9	98.0	1.4	5.2	19,000 lb.
1,000	97.8	98.0	98.1	1.4	5.2	21,000 lb.

99. Single-phase—25 Cycles—11,000-volt Class

Kv-a.	Efficiencies			Regulation		Net weight including oil
	½ load	¾ load	Full load	100% p. f.	80% p. f.	
125	96.5	96.8	96.7	2.2	4.0	4,700 lb.
150	96.8	97.0	96.9	2.1	3.9	4,900 lb.
200	97.1	97.3	97.2	2.0	3.8	6,500 lb.
333	97.3	97.5	97.4	1.8	3.6	9,000 lb.
400	97.5	97.7	97.6	1.6	3.5	11,000 lb.
500	97.7	97.9	97.8	1.5	3.4	13,000 lb.

100. Single-phase—25 Cycles—22,000-volt Class

Kv-a.	Efficiencies			Regulation		Net weight including oil
	½ load	¾ load	Full load	100% p. f.	80% p. f.	
125	96.4	96.7	96.6	2.4	4.5	6,000 lb.
150	96.7	96.9	96.8	2.3	4.4	6,300 lb.
200	97.0	97.2	97.1	2.1	4.3	7,300 lb.
333	97.2	97.4	97.3	1.9	4.1	10,300 lb.
400	97.4	97.6	97.5	1.8	4.0	12,500 lb.
500	97.6	97.8	97.7	1.6	3.9	13,500 lb.

101. Single-phase—25 Cycles—33,000-volt Class

Kv-a.	Efficiencies			Regulation		Net weight including oil
	½ load	¾ load	Full load	100% p. f.	80% p. f.	
125	96.3	96.5	96.4	2.6	5.0	6,600 lb.
150	96.6	96.8	96.6	2.5	5.0	6,800 lb.
200	96.9	97.1	96.9	2.4	4.9	7,500 lb.
333	97.2	97.3	97.2	2.1	4.6	11,500 lb.
400	97.4	97.5	97.4	1.8	4.5	13,000 lb.
500	97.5	97.7	97.6	1.7	4.3	14,000 lb.

102. Single-phase—25 Cycles—44,000-volt Class

Kv-a.	Efficiencies			Regulation		Net weight including oil
	½ load	¾ load	Full load	100% p. f.	80% p. f.	
125	96.0	96.2	96.0	3.1	5.6	6,700 lb.
150	96.4	96.5	96.3	2.7	5.3	6,900 lb.
200	96.7	96.8	96.6	2.5	5.1	8,100 lb.
333	97.0	97.2	97.0	2.3	5.0	11,500 lb.
400	97.3	97.5	97.3	2.0	4.8	13,500 lb.
500	97.4	97.6	97.5	1.8	4.6	16,000 lb.

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103. Tables giving ratings, efficiencies, regulation and weights of standard oil-insulated water-cooled transformers. The rise of temperature of these transformers above incoming water is 55 deg. cent. with continuous full load. They are "maximum rated" units in accordance with the Standardization Rules of the A. I. E. E.

104. Single-phase—60 Cycles—22,000-volt Class

Kv-a.	Efficiencies			Regulation		Net weight with oil	Water rate: gal. per min.
	½ load	¾ load	Full load	100% p. f.	80% p. f.		
1,000	98.1	98.25	98.2	1.4	4.6	8,000 lb.	5
1,250	98.15	98.3	98.25	1.35	4.6	9,200 lb.	6
1,667	98.25	98.4	98.35	1.30	4.6	10,600 lb.	7
2,000	98.35	98.5	98.45	1.25	4.6	11,600 lb.	8
2,500	98.4	98.55	98.55	1.25	4.6	13,800 lb.	10
3,333	98.55	98.65	98.65	1.10	4.2	17,500 lb.	12
5,000	98.65	98.8	98.8	1.10	4.2	23,000 lb.	15

105. Single-phase—60 Cycles—44,000-volt Class

Kv-a.	Efficiencies			Regulation		Net weight with oil	Water rate: gal. per min.
	½ load	¾ load	Full load	100% p. f.	80% p. f.		
1,000	97.7	97.95	97.95	1.45	5.5	11,300 lb.	6.0
1,250	97.9	98.1	98.1	1.4	5.5	12,500 lb.	6.0
1,667	98.05	98.25	98.2	1.35	5.5	13,700 lb.	7.5
2,000	98.15	98.35	98.35	1.25	5.5	15,000 lb.	9.0
2,500	98.3	98.5	98.45	1.15	5.5	17,000 lb.	10.0
3,333	98.45	98.6	98.55	1.05	5.0	20,500 lb.	12.0
5,000	98.55	98.7	98.7	1.00	4.5	27,500 lb.	17.0

106. Single-phase—60 Cycles—66,000-volt Class

Kv-a.	Efficiencies			Regulation		Net weight with oil	Water rate: gal. per min.
	½ load	¾ load	Full load	100% p. f.	80% p. f.		
1,000	97.55	97.85	97.85	1.55	6.0	14,700 lb.	6.0
1,250	97.7	97.95	97.95	1.45	6.0	15,500 lb.	6.5
1,667	97.9	98.15	98.15	1.35	6.0	17,700 lb.	8.0
2,000	98.05	98.25	98.25	1.25	6.0	19,000 lb.	9.0
2,500	98.2	98.4	98.4	1.20	5.5	21,000 lb.	10.5
3,333	98.3	98.5	98.5	1.20	5.5	25,000 lb.	13.0
5,000	98.45	98.65	98.65	1.10	5.0	32,500 lb.	17.0

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107. Single-phase—60 Cycles—88,000-volt Class

Kv-a.	Efficiencies			Regulation		Net weight with oil	Water rate: gal. per min.
	½ load	¾ load	Full load	100% p. f.	80% p. f.		
1,000	97.5	97.75	97.75	1.70	6.5	18,000 lb.	6.0
1,250	97.65	97.9	97.9	1.70	6.5	20,000 lb.	7.0
1,667	97.75	98.05	98.05	1.60	6.5	22,000 lb.	8.5
2,000	97.95	98.2	98.2	1.55	6.5	24,000 lb.	9.5
2,500	98.1	98.35	98.35	1.45	6.0	27,000 lb.	11.0
3,333	98.25	98.45	98.45	1.40	5.5	30,000 lb.	13.5
5,000	98.35	98.55	98.55	1.35	5.5	37,000 lb.	18.5

108. Single-phase—60 Cycles—110,000-volt Class

Kv-a.	Efficiencies			Regulation		Net weight with oil	Water rate: gal. per min.
	½ load	¾ load	Full load	100% p. f.	80% p. f.		
1,000	97.35	97.65	97.65	1.8	6.5	25,000 lb.	6
1,250	97.5	97.8	97.8	1.7	6.5	28,000 lb.	7
1,667	97.7	97.95	97.95	1.6	6.5	32,000 lb.	9
2,000	97.85	98.1	98.1	1.5	6.5	34,000 lb.	10
2,500	98.05	98.3	98.3	1.45	6.0	37,000 lb.	11
3,333	98.15	98.35	98.35	1.40	6.0	40,000 lb.	14
5,000	98.3	98.5	98.45	1.35	5.8	48,000 lb.	20

109. Single-phase—60 Cycles—132,000-volt Class

Kv-a.	Efficiencies			Regulation		Net weight with oil	Water rate: gal. per min.
	½ load	¾ load	Full load	100% p. f.	80% p. f.		
5,000	98.25	98.45	98.4	1.50	6.0	55,000 lb.	22
10,000	98.65	98.75	98.7	1.45	6.2	65,000 lb.	35
16,667	98.75	98.85	98.85	1.30	6.6	90,000 lb.	50

110. Single-phase—60 Cycles—154,000-volt Class

Kv-a.	Efficiencies			Regulation		Net weight with oil	Water rate: gal. per min.
	½ load	¾ load	Full load	100% p. f.	80% p. f.		
10,000	98.45	98.65	98.7	1.45	6.5	100,000 lb.	35
16,667	98.6	98.75	98.8	1.35	7.0	140,000 lb.	55

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111. Single-phase—60 Cycles—220,000-volt Class

Kv-a.	Efficiencies			Regulation		Net weight with oil	Water rate: gal. per min.
	½ load	¾ load	Full load	100% p. f.	80% p. f.		
16,667	98.2	98.45	98.45	1.7	8.0	190,000 lb.	70
23,300	98.45	98.65	98.65	1.75	9.0	225,000 lb.	85
30,000	98.5	98.7	98.7	1.65	9.0	250,000 lb.	100

112. Single-phase—25 Cycles—22,000-volt Class

Kv-a.	Efficiencies			Regulation		Net weight with oil	Water rate: gal. per min.
	½ load	¾ load	Full load	100% p. f.	80% p. f.		
1,000	97.6	97.8	97.75	1.6	4.2	12,600 lb.	7.0
1,250	97.75	97.95	97.90	1.55	4.2	14,800 lb.	7.0
1,667	97.90	98.10	98.05	1.45	4.2	17,300 lb.	8.5
2,000	97.95	98.15	98.10	1.45	4.5	19,000 lb.	10.0
2,500	98.10	98.25	98.20	1.40	5.0	23,200 lb.	12.0
3,333	98.15	98.35	98.3	1.35	5.6	28,000 lb.	15.0
5,000	98.25	98.45	98.40	1.35	6.0	40,000 lb.	20.0

113. Single-phase—25 Cycles—44,000-volt Class

Kv-a.	Efficiencies			Regulation		Net weight with oil	Water rate: gal. per min.
	½ load	¾ load	Full load	100% p. f.	80% p. f.		
1,000	97.35	97.6	97.5	1.85	4.5	16,500 lb.	7.0
1,250	97.55	97.75	97.7	1.70	4.5	18,300 lb.	7.5
1,667	97.7	97.9	97.85	1.60	4.5	21,400 lb.	9.0
2,000	97.8	98.0	97.95	1.55	4.5	23,200 lb.	10.5
2,500	97.95	98.15	98.10	1.50	5.0	26,500 lb.	12.5
3,333	98.1	98.25	98.20	1.45	5.6	32,000 lb.	16.0
5,000	98.15	98.35	98.35	1.40	6.0	44,500 lb.	22.0

114. Single-phase—25 Cycles—66,000-volt Class

Kv-a.	Efficiency			Regulation		Net weight with oil	Water rate: gal. per min.
	½ load	¾ load	Full load	100% p. f.	80% p. f.		
1,000	97.15	97.4	97.3	1.95	5.0	20,000 lb.	7
1,250	97.4	97.6	97.55	1.8	5.0	21,600 lb.	8
1,667	97.6	97.8	97.75	1.7	5.0	25,400 lb.	10
2,000	97.7	97.9	97.85	1.65	5.0	28,000 lb.	12
2,500	97.9	98.1	98.05	1.55	6.0	30,000 lb.	13
3,333	98.0	98.2	98.1	1.5	6.0	35,700 lb.	18
5,000	98.1	98.3	98.25	1.45	6.5	49,500 lb.	24

TRANSFORMERS FOR DISTRIBUTING SYSTEMS

115. General considerations in design. Transformers for distributing systems should be of high efficiency. Competition has brought about a certain degree of standardization of the losses of each size of transformer. The problem is, therefore, to produce a design having a minimum cost which is durable in service and conforms to definite performance specifications.

116. The relative values of core-loss and copper-loss in lighting transformers have been largely determined by competition, but it is probable that the present values give about the best average results in service.

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117. The two types of transformers, viz., the shell-type and the core-type are both used for distributing transformers. The form of shell-type shown in Fig. (8) has shorter mean length of winding and magnetic circuit than the usual form. The dividing line between shell-type and core-type design depends both upon voltage and rating. The former being more economical for low-voltages and large ratings and the latter for high voltage and low ratings. It is usual however to have one type for a line of transformers. The core-type is better adapted for direct cooling in air than the shell-type.

118. Standard lighting and power transformers are designed for operation on 60-cycle circuits and have a nominal primary voltage of 2,300 volts and secondary voltages of 230 volts and 115 volts, or 460 and 230 volts. The **temperature guarantees** for these transformers are usually 45 deg. cent. above atmosphere after 8 hr. full-load run, and 55 deg. after continuous full-load run. Some manufacturers guarantee a temperature rise of 60 deg. cent. at 25 per cent. overload for 4 hr., starting with the oil temperature obtained under no-load conditions. The **insulation test** is usually 10,000 volts, for 1 min., between high-tension and low-tension windings and ground; an overpotential test varying with different manufacturers from double to five times normal voltage is also applied.

119. Ratings and efficiencies. The accompanying data (Par. **120** to Par **123**) on standard lighting transformers have been chosen as giving a fair representation of the general practice in the United States. Two type. are manufactured for 2,300-volt 60-cycle service, namely, a "High-efficiency Type" or (standard) and a "Low-efficiency Type." The former type should be used when the cost of energy is high and when it is desirable to operate at high efficiency both all-day and underload. The latter type is justifiable for installation when the cost of energy is low, and where it is not so essential to have a high-operating efficiency. The table (Par. **120**) gives performances of "standard" or "High-efficiency" lighting transformers.* The remaining **60-cycle transformers are designed for operation on circuits of higher voltage than 2,300 volts and therefore have correspondingly lower performances.**

120. Performances of 60-cycle Lighting Transformers: Standard Voltages 2,300 to 230/115 or 460/230

Kv-a.	Iron loss (watts)	Copper loss (watts)	Per cent. efficiency				Per cent. regulation		Outline dimensions		Approx. net weight of transformers
			Full load	¾ load	½ load	¼ load	100 % p. f.	80 % p. f.	Floor space	Height	
1	21	29	95.2	95.2	94.1	91.6	3.1	3.2	9½ × 14½	11	80
2	30	52	96.0	96.2	95.8	93.8	2.5	2.8	12 × 16	13	120
3	35	76	96.4	96.6	96.5	95.0	2.4	3.0	12 × 16	14	150
5	44	99	97.2	97.4	97.2	95.1	2.1	2.9	14 × 18	16½	225
7.5	60	128	97.5	97.7	97.5	96.5	1.8	2.8	15½ × 19½	18	310
10	74	168	97.6	97.8	97.7	96.7	1.8	2.7	15½ × 19½	21	360
15	103	222	97.8	98.0	97.9	96.9	1.6	2.6	15½ × 19½	28½	490
25	137	367	98.0	98.2	98.1	97.4	1.6	2.6	22 × 24	30½	790
37.5	200	490	98.2	98.3	98.2	97.5	1.5	2.8	24 × 28½	37½	1070
50	258	607	98.3	98.4	98.3	97.6	1.3	2.7	24 × 28½	44½	1280
75	460	825	98.3	98.3	98.2	97.3	1.15	2.55	30½ × 37½	39½	1680
100	615	1120	98.3	98.3	98.2	97.3	1.20	2.60	30½ × 37½	48½	1820
150	840	1800	98.2	98.3	98.2	97.5	1.30	3.15	34 × 40½	69	2480
200	1130	2400	98.2	98.3	98.2	97.5	1.30	3.15	34 × 40½	75	2560

* The iron loss is measured by wattmeter, and the copper loss is measured by wattmeter and corrected to 75 deg. cent.

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121. Performance of 25-cycle Transformers: Standard Voltages 2,300 to 230/115

Kv-a.	Iron loss (watts)	Copper loss (watts)	Per cent. efficiency				Per cent. regulation		Outline dimensions		Approx. net weight of transformers
			Full load	¾ load	½ load	¼ load	100 % p. f.	80 % p. f.	Floor space	Height	
1	22	48	93.4	93.8	93.6	90.9	4.9	5.2	12 ×16	13	110
2	39	75	94.6	94.8	94.5	91.9	3.9	4.5	14 ×18	16	130
3	48	100	95.3	95.6	95.3	93.2	3.4	4.0	14 ×18	16	160
5	71	150	95.8	96.0	95.8	93.9	3.1	3.9	15½ ×19½	18	220
7.5	101	187	96.3	96.4	96.1	94.3	2.6	3.4	20 ×23	22	340
10	124	240	96.5	96.6	96.6	94.7	2.5	3.4	22 ×24½	22	425
15	154	326	96.9	97.1	96.9	95.5	2.3	3.0	22 ×24½	31	545
25	250	438	97.3	97.4	97.2	95.7	1.9	2.6	24 ×28½	37½	820
37.5	274	760	97.3	97.5	97.5	96.6	2.1	2.8	31 ×33	39	1630
50	325	955	97.5	97.7	97.7	96.9	2.0	2.8	31 ×33	45½	1690
75	450	1550	97.4	97.7	97.8	97.1	2.2	2.8	34 ×40½	51	2150
100	580	2100	97.4	97.7	97.7	97.2	2.2	2.7	34 ×40½	74	2700
150	1520	2400	97.4	97.5	97.2	95.7	1.7	2.9	33 ×33	81	3370
200	1750	3500	97.4	97.6	97.4	96.2	1.8	3.0	39 ×39	71	4500

122. Performance of 60-cycle Transformers: Standard Voltages 6,900–6,585–6,275 to 230/115 or 460/230

Kv-a.	Iron loss (watts)	Copper loss (watts)	Per cent. efficiency				Per cent. regulation		Outline dimensions		Approx. net weight of transformers
			Full load	¾ load	½ load	¼ load	100 % p. f.	80 % p. f.	Floor space	Height	
1.5	34	55	94.4	94.6	94.0	90.9	3.7	4.15	11½ ×16½	18½	140
3	48	87	95.7	95.9	95.5	93.3	3.1	3.85	12 ×18½	21½	190
5	55	150	96.1	96.4	96.4	95.1	3.05	3.50	13 ×20	23	240
7.5	79	200	96.4	96.7	96.6	95.3	2.7	3.1	15½ ×22½	25½	346
10	102	220	96.9	97.1	96.9	95.6	2.2	2.55	15½ ×22½	26	380
15	123	314	97.2	97.4	97.3	96.3	2.1	2.65	17 ×24½	31	540
25	172	476	97.5	97.7	97.7	96.9	1.95	2.75	21½ ×31	36	850
37.5	230	624	97.8	98.0	98.0	97.2	1.75	2.85	23 ×33	42	1080
50	270	787	98.0	98.1	98.1	97.5	1.65	2.6	24½ ×35½	48	1540
75	417	1035	98.1	98.3	98.2	97.5	1.45	2.6	30½ ×37	58	1810
100	655	1150	98.2	98.2	98.1	97.1	1.25	2.45	34 ×40½	56	2170
150	820	1960	98.2	98.3	98.2	97.5	1.40	2.50	34 ×40½	69	2600
200	1200	2500	98.2	98.3	98.2	97.3	1.3	2.5	34 ×40½	80	2670

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23. Performance of 60-cycle Transformers: Standard Voltages 11,500–10,925–10,350 to 230/115 or 460/230

Kv-a.	Iron loss (watts)	Copper loss (watts)	Per cent. efficiency				Per cent. regulation		Outline dimensions		Approx. net weight of transformers
			Full load	¾ load	½ load	¼ load	100 % p. f.	80 % p. f.	Floor space	Height	
2.5	49	72	95.4	95.4	94.9	92.1	2.9	4.0	13 ×22	26	286
5	72	139	95.9	96.1	95.9	93.9	2.9	3.8	15 ×24½	27½	376
10	134	258	96.2	96.4	96.1	94.3	2.7	3.6	15 ×24½	27½	420
15	155	320	96.9	97.1	96.9	95.5	2.1	3.1	17 ×25½	32½	580
25	232	430	97.4	97.5	97.3	96.0	1.8	2.9	21½ ×31	36	850
37.5	300	605	97.6	97.7	97.6	96.5	1.7	2.8	23 ×33	42	1080
50	348	745	97.9	98.0	97.9	97.0	1.6	2.7	24½ ×35½	48	1390
75	663	950	97.9	97.9	97.6	96.3	1.4	2.5	30½ ×37	58½	1800
100	819	1210	98.0	98.0	97.7	96.5	1.3	2.5	34 ×40½	51	2150
150	1162	1440	98.3	98.3	98.0	96.8	1.1	2.6	34 ×40½	69	2600
200	1200	2400	98.2	98.3	98.1	97.3	1.1	2.6	34 ×40½	80	3010

24. Performance of 60-cycle Transformers: Standard Voltages 12,800–12,110–12,420 to 460/230 or 230/115

Kv-a.	Iron loss (watts)	Copper loss (watts)	Per cent. efficiency				Per cent. regulation		Outline dimensions		Approx. net weight of transformers
			Full load	¾ load	½ load	¼ load	100 % p. f.	80 % p. f.	Floor space	Height	
2.5	53	69	95.3	95.4	94.7	91.6	2.8	3.7	13 ×22	26	286
5	89	124	95.9	96.0	95.4	92.8	2.6	3.5	15 ×24½	27½	375
10	134	240	96.4	96.5	96.2	94.4	2.5	3.5	15 ×24½	27½	420
15	176	318	96.8	96.9	96.7	95.1	2.2	3.2	17 ×25½	32½	575
25	263	392	97.4	97.5	97.2	95.7	1.7	2.8	21½ ×31	36	853
37.5	338	569	97.6	97.7	97.5	96.2	1.6	2.7	23 ×33	42	1081
50	383	765	97.8	97.9	97.7	96.7	1.6	2.7	24½ ×35½	48	1390
75	559	1040	97.9	98.0	97.8	96.8	1.5	2.6	30½ ×37	58½	1800
100	692	1165	98.2	98.3	98.0	97.0	1.3	2.5	34 ×40½	51	2150
150	960	1860	98.2	98.1	98.2	97.2	1.3	2.5	34 ×40½	69	2600
200	1200	2400	98.2	98.3	98.1	97.3	1.3	2.5	34 ×40½	80	3000

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125. Performance of 60-cycle Transformers: Standard Voltages 22,000–21,850–20,700 to 460/230 or 230/115

Kv-a.	Iron loss (watts)	Copper loss (watts)	Per cent. efficiency: Full load	¾ load	½ load	¼ load	Per cent. regulation: 100% p. f.	80% p. f.	Outline dimensions: Floor space	Height	Approx. net weight of transformers
5	145	140	94.6	94.9	93.3	89.1	2.9	4.3	21 ×30	38	500
10	247	228	95.5	95.3	95.3	90.2	2.4	3.4	24 ×33	39½	720
15	324	281	96.2	95.9	95.0	91.6	2.0	3.0	25½ ×34	41	830
25	324	430	97.0	97.0	96.6	94.7	1.8	2.9	27½ ×35	42½	1150
37.5	592	547	97.5	96.9	96.3	93.8	1.6	2.7	29 ×37	47½	1360
50	635	695	97.4	97.3	96.8	94.7	1.5	2.7	32 ×35	49	1660
75	882	930	97.7	97.2	97.2	95.3	1.3	2.5	35½ ×36½	56½	2040
100	960	1300	97.8	97.8	97.5	96.0	1.4	2.6	35½ ×36½	64	2270
150	1443	1865	97.9	97.9	97.5	96.0	1.3	2.5	40 ×44	63	2930
200	1532	2240	98.5	98.2	98.0	97.8	1.2	2.4	40 ×44	80	3440

126. Manhole transformers. It is the general practice in large cities to supply energy for lighting by means of underground cables. Manhole transformers are simply lighting transformers fitted with cases of a type suited for operation in a manhole. These cases are rendered water-tight and air-tight and have an extra amount of radiating surface. The cover is provided with a vent covered by a thin air-tight metal diaphragm, so that if the pressure in the case becomes excessive the diaphragm will rupture. The outlet bushings should be so designed that they are moisture proof and yet admit of ready disconnection of the transformer. The rating, efficiency and regulation are the same as for standard distributing transformers.

MULTIPLE OPERATION

127. General principles. In Par. **19** of this section it is shown that the transformer of unity ratio may be represented by a simple alternating-current circuit shunted by an admittance Y. Where the ratio is not unity, this equivalent circuit still holds, if one winding is taken as the reference winding and all admittances are reduced to terms of this winding; this may be done by multiplying (or dividing) all these quantities in the other winding by the square of the ratio. The admittance Y does not enter the problem of relative division of the load and may therefore be ignored; the effective impedance of the transformer with respect to the reference winding will then be the same as the short-circuit impedance with that winding considered as the primary and the other short-circuited.

It is shown in Sec. 2, that in a branched circuit the current in each branch will be inversely proportional to the impedance of the branch. Since the effects of the primary and the secondary resistance and the magnetic leakage of the transformer may be represented by a simple impedance the rule of branch circuits will also apply to parallel operation of transformers. In actual calculations the problem is usually to determine how a given number of transformers will divide a load of given kv-a. and power factor. It will be found convenient in most cases, instead of using actual impedances or admittances, to use the ohmic and reactance drops expressed as fractions of the secondary voltage. Admittances derived from these are proportional to the actual admittance.

128. Formulas. Let the kv-a. rating of the transformers be P_1, P_2, P_3, etc., and let the impedance volts of each, expressed as a fraction of the rated voltage, be (c_1+jd_1), (c_2+jd_2), (c_3+jd_3), etc., respectively, then the admittances (g_1-jb_1), (g_2-jb_2), (g_3-jb_3), etc., will have the following values

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$$\left.\begin{aligned} g_1 &= \left(\frac{c_1}{c_1^2+d_1^2}\right)\cdot\left(\frac{P_1}{P_1+P_2+P_3+}\right);\ b_1 = \left(\frac{d_1}{c_1^2+d_1^2}\right)\cdot\left(\frac{P_1}{P_1+P_2+P_3+}\right) \\ g_2 &= \left(\frac{c_2}{c_2^2+d_2^2}\right)\cdot\left(\frac{P_2}{P_1+P_2+P_3+}\right);\ b_2 = \left(\frac{d_2}{c_2^2+d_2^2}\right)\cdot\left(\frac{P_2}{P_1+P_2+P_3+}\right) \\ g_3 &= \left(\frac{c_3}{c_3^2+d_3^2}\right)\cdot\left(\frac{P_3}{P_1+P_2+P_3+}\right);\ b_3 = \left(\frac{d_3}{c_3^2+d_3^2}\right)\cdot\left(\frac{P_3}{P_1+P_2+P_3+}\right) \end{aligned}\right\} \quad (39)$$

The joint admittance Y is equal to the sum of all the admittances, or

$$Y = g - jb = g_1 + g_2 + g_3 + \ \ldots\ - j(b_1 + b_2 + b_3 + \ \ldots\ ) \quad (40)$$

The loads taken by the first, second, and third transformers expressed as fractions of the total kv-a. are respectively

$$\frac{\sqrt{g_1^2+b_1^2}}{\sqrt{g^2+b^2}},\qquad \frac{\sqrt{g_2^2+b_2^2}}{\sqrt{g^2+b^2}},\qquad \frac{\sqrt{g_3^2+b_3^2}}{\sqrt{g^2+b^2}} \quad (41)$$

The power-factor of the load supplied by the transformers when the power-factor of the combined load is cos α are respectively

$$\cos(\alpha+\theta_1-\theta),\ \cos(\alpha+\theta_2-\theta),\ \cos(\alpha+\theta_3-\theta) \quad (42)$$

where θ, θ_1 and θ_2 are given by

$$\theta = \tan^{-1}\frac{b}{g} \qquad \theta_1 = \tan^{-1}\frac{b_1}{g_1} \qquad \theta_2 = \tan^{-1}\frac{b_2}{g_2}, \text{ etc.} \quad (43)$$

129. When the transformation ratios of two transformers are slightly different they may be operated in multiple, without incurring much trouble. The currents I_1 and I_2 taken by the two transformers will depend upon the transformation ratios m_1 and m_2, the two transformer impedances Z_1 and Z_2 and the load impedance Z_0. The following formulas may be readily used by those familiar with complex imaginary quantities:

$$\left.\begin{aligned} I_1 &= \frac{m_1 Z_2 + (m_1 - m_2) Z_0}{Z_1 Z_2 + Z_0(Z_1 + Z_2)} V_0 \\ I_2 &= \frac{m_2 Z_1 - (m_1 - m_2) Z_0}{Z_1 Z_2 + Z_0(Z_1 + Z_2)} V_0 \end{aligned}\right\} \quad (44)$$

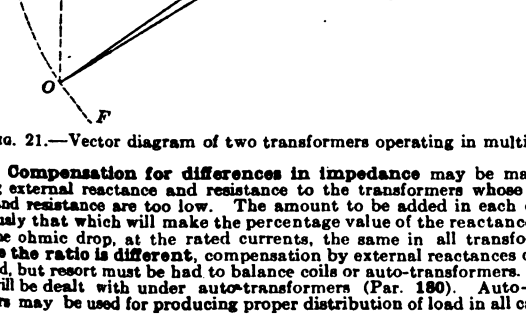


FIG. 21.—Vector diagram of two transformers operating in multiple.

130. Compensation for differences in impedance may be made by adding external reactance and resistance to the transformers whose reactance and resistance are too low. The amount to be added in each case is obviously that which will make the percentage value of the reactance drop and the ohmic drop, at the rated currents, the same in all transformers. **Where the ratio is different**, compensation by external reactances cannot be used, but resort must be had to balance coils or auto-transformers. This case will be dealt with under auto-transformers (Par. 180). Auto-transformers may be used for producing proper distribution of load in all cases.

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131. Explanation of vector diagram, Fig. 21, for multiple operation. In the above diagram AB is taken of any arbitrary length to represent the combined impedance drop. AD_1 and AD_2 are each taken the same fraction of AB that the resistance drops of the respective transformers bear to their impedance drops. AC_1 is taken equal to the current that will produce the drop AD_1 in one transformer, and AC_2 is taken equal to the current that will produce the drop AD_2 in the other transformer. The resultant AC is the combined current. The corresponding combined resistance drop is AD. The line AC will then represent the combined load current on a certain scale, and AC_1 and AC_2 will represent the currents in the respective transformers, in magnitude and phase, on the same scale. Since the currents are known, the value of the impedance drop is known, and therefore the scale on which AB represents the impedance drop is known also: we may take a certain length to represent the magnitude of the secondary open-circuit voltage on the same scale, and with B as a centre strike an arc EOF; then, extending CA to E, draw AO, making the angle α with AE, where $\cos\alpha$ is the power-factor of the load. OA represents the secondary terminal voltage and OB represents the secondary open-circuit voltage, or approximately the primary e.m.f. multiplied by the ratio of transformation, and with phase reversed.

POLYPHASE TRANSFORMATIONS

132. General considerations. A polyphase system is classified as a **balanced n-phase system** when the e.m.fs. and currents in corresponding branches at every point of the system are sinusoidal, have equal effective values, and differ in phase by $1/n$th of a period. If $\mathcal{E}_1$ be one of the e.m.fs. and 1, α_1, α_2, . . . are the n roots of the equation $x^n - 1 = 0$, the balanced n-phase system of e.m.fs. may be expressed symbolically as follows:

$$\mathcal{E}_1 = \mathcal{E}_1, \quad \mathcal{E}_2 = \alpha_1\mathcal{E}_1, \quad \mathcal{E}_3 = \alpha_2\mathcal{E}_1 \ldots . \mathcal{E}_n = \alpha_{n-1}\mathcal{E}_1 \tag{45}$$

In such a system

$$\mathcal{E}_1 + \mathcal{E}_2 + \mathcal{E}_3 + \ldots \ldots + \mathcal{E}_n = 0 \tag{46}$$

133. A symmetrical n-phase system of currents or e.m.fs. is one in which the effective values of all the constituents are equal and when taken in fixed order or sequence, they differ in phase by any integral multiple of $2\pi/n$ from zero to $(n-1)$. That system for which the integral multiplier is zero is termed a zero phase-sequence system; that for which the integral multiplier is unity is called a system of phase sequence one. In a **three-phase system** the second phase sequence is the same as the first with sequence reversed; it is convenient to call the first phase sequence the **positive phase sequence** and the second the **negative phase sequence.**

134. An unbalanced polyphase system is one in which the e.m.fs. or currents in any part of the system are unequal in effective value or are unsymmetrical in phase-relation. The unbalanced currents and e.m.fs. may be resolved uniquely into n symmetrical systems of zero, 1st, 2d, 3d . . . $(n-1)$th phase sequence, each of which may be considered independently of the remaining systems, so that the problem reduces to the solution of n symmetrical systems.

135. The resolution of an unbalanced system of 3-phase currents or e.m.fs. into its symmetrical components may be effected very simply; thus if the currents in phase A, B and C be I_A, I_B and I_C respectively and the zero phase sequence, positive phase sequence and negative phase sequence components in phase A be I_{A0}, I_{A1} and I_{A2} respectively, and if 1, α and α^2 are the cube-roots of unity or 1, $\left(-\frac{1}{2}+j\frac{\sqrt{3}}{2}\right)$, and $\left(-\frac{1}{2}-j\frac{\sqrt{3}}{2}\right)$ respectively,

$$\left.\begin{aligned} I_{A0} &= \frac{I_A + I_B + I_C}{3} \\ I_{A1} &= \frac{I_A + \alpha I_B + \alpha^2 I_C}{3} \\ I_{A2} &= \frac{I_A + \alpha^2 I_B + \alpha I_C}{3} \end{aligned}\right\} \tag{47}$$

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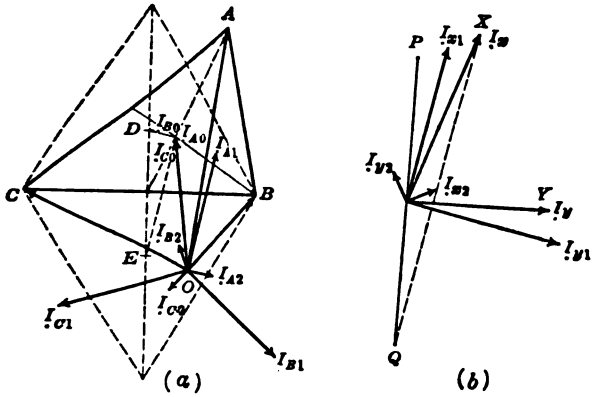


FIG. 22.—Graphic resolution of three-phase (a) and two-phase unbalanced systems into symmetrical systems.

136. The resolution may be done graphically as follows. In Fig. 22(a) let OA, OB, and OC represent in magnitude and phase the line currents I_A, I_B and I_C respectively. The line drawn from O to the center of the triangle ABC will represent in magnitude and phase the zero phase-sequence component I_{A0}. Erect on both sides of BC an equilateral triangle; draw a line from O equal and parallel to the line joining the centroid of the equilateral triangle on BC having its apex on the opposite side to A, to the centroid of the triangle ABC; this line will represent I_{A1} in magnitude and phase. The line drawn through O parallel and equal to that joining the centroid of the other equilateral triangle to the centroid of ABC will represent I_{A2} in magnitude and phase.

137. Phase "A" is termed the principal phase and all the members of any given phase sequence are expressed in terms of the component in Phase A.

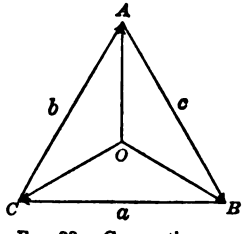


FIG. 23.—Conventions used for directions of e.m.fs. and of current flow in symmetrical components.

138. The delta symmetrical components of current and e.m.f. bear simple relations to the corresponding star components. Using the usual trigonometrical conventions for the angles and sides of the triangle ABC, the positive direction for star being outward from O and for delta from A to B, B to C and C to A, as indicated in Fig. 23,

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$$\left.\begin{aligned} E_{a0} &= 0 & I_{a0} &= \text{indefinite} \\ E_{a1} &= +j\sqrt{3}E_{A1} & I_{a1} &= +j\frac{I_{A1}}{\sqrt{3}} \\ E_{a2} &= -j\sqrt{3}E_{A2} & I_{a2} &= -j\frac{I_{A2}}{\sqrt{3}} \end{aligned}\right\} \quad (48)$$

139. The two-phase system is in reality a four-phase system so constrained that unbalancing does not involve components of zero and second phase sequences, but where the two phases are interconnected electrically through connections between transformer windings or in rotating apparatus it becomes a true four-phase system and must be dealt with accordingly.

140. In the simple two-phase system without interconnections if I_x and I_y are the currents in the two phases, they may be resolved into the two component systems of positive and negative phase sequence for which the currents in the x phase are

$$\left.\begin{aligned} I_{x1} &= \frac{I_x + jI_y}{2} \\ I_{x2} &= \frac{I_x - jI_y}{2} \end{aligned}\right\} \quad (49)$$

The solution is graphically carried out as follows. In Fig. 22(*b*) let OX and OY represent in magnitude and phase the currents I_x and I_y respectively. Draw a line OP equal to and at an angle $\pi/2$ in advance of OY; then the line joining O to the middle point of PX represents in magnitude and phase the member of the positive phase sequence component in the X phase, namely I_{x1}. Draw a line OQ equal to OY and lagging $\pi/2$ behind OY. The line OX_2 drawn from O to the middle point of QX will represent in magnitude and phase I_{x2}, the member of the X phase of the negative phase sequence component of the two-phase system of currents.

141. The zero phase sequence component does not enter into polyphase transformations except where there are connections to ground or where an ungrounded system has unsymmetrical admittance to ground. The zero phase sequence component of current will appear also in unsymmetrical delta or ring connections. When the zero phase sequence components of current appear in the lines due to ground connections or unsymmetrical ground admittances, while otherwise negligible, they may give rise to inductive interference with near-by communication circuits and they are commonly known to telephone engineers as residual currents.

142. Except when considering the effects of grounds on the system, only the positive and negative phase sequence components of a three-phase system will be considered.

143. A convenient method of calculating simple unbalanced transformer connections is to consider the effect of each symmetrical component in the system separately, expressing each member in terms of that of the principal phase, and the currents in the delta connections in terms of the line currents by means of the relations in Eq. 48 in Par. 138. The e.m.fs. may then be resolved into symmetrical components with Phase A as the principal phase by Eq. 47. For more direct methods see "Symmetrical Co-ordinates Applied to the Solution of Polyphase Networks," by Fortescue, C. L. G., *Trans.* A. I. E. E., Vol. XXXVII, Part 2, p. 1027.

144. In this sub-section we shall confine ourselves to the unbalancing effect of unsymmetrical transformation, and to a few cases of **grounding.** The general problem of unbalancing of polyphase systems belongs properly to **Polyphase Networks.**

145. Two-phase to two-phase transformation. The usual transformation is effected in each phase independently by means of a transformer; the four secondary leads are independent, forming the terminals of a four-wire non-interlinked two-phase system. If the middle points of the secondary windings are connected together the four-wire symmetrical interlinked two-phase system is obtained. If two ends of the secondary winding are connected together the **two-phase three-wire system** results, which is an

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interlinked unsymmetrical polyphase system not well adapted for long distance transmission. In this system the e.m.f. between the other two ends of the windings is $\sqrt{2}$ times the e.m.f. across the windings. Fig. 24 illustrates these systems.

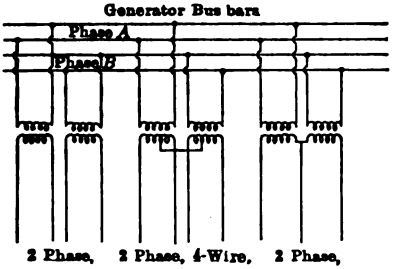


FIG. 24.—Two-phase systems.

146. Transformations between two-phase and three-phase systems. The most usual arrangement of transformers is that shown in

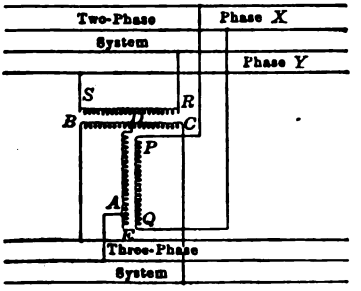


FIG. 25.—"Scott connection", two-phase to three-phase or three-phase to two-phase.

Fig. 25. The two transformers DQ and BR are usually of like design, both being provided with a tap at the middle point of one winding and also one at a point $\sqrt{3}/2$ or 0.866 of the winding from one end, as shown at D and A respectively. When the transformers are supplying balanced currents, the current density in the working portions of the windings of both transformers is the same. The transformer DQ has 13.4 per cent. less loss in the winding DE than the transformer BR. The unbalance due to the tap A being inaccurately located is best shown by expressing the transformation equations in symmetrical components. Thus if $\mathfrak{E}_{A1}$ and $\mathfrak{E}_{A2}$ are the symmetrical components of the three-phase e.m.fs. measured from the neutral, and $\mathfrak{E}_{x1}$ and $\mathfrak{E}_{x2}$ are those of the two-phase system, and if m be the ratio of the winding DA to the whole, and ρ the ratio of transformation from RS' to BC,

$$\left.\begin{aligned}\mathfrak{E}_{A1} &= \rho\left\{\frac{\mathfrak{E}_{x1}}{\sqrt{3}}\left(\frac{m}{\sqrt{3}}+\frac{1}{2}\right)+\frac{\mathfrak{E}_{x2}}{\sqrt{3}}\left(\frac{m}{\sqrt{3}}-\frac{1}{2}\right)\right\}\\ \mathfrak{E}_{A2} &= \rho\left\{\frac{\mathfrak{E}_{x1}}{\sqrt{3}}\left(\frac{m}{\sqrt{3}}-\frac{1}{2}\right)+\frac{\mathfrak{E}_{x2}}{\sqrt{3}}\left(\frac{m}{\sqrt{3}}+\frac{1}{2}\right)\right\}\end{aligned}\right\} \quad (50)$$

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Thus if the transformation is from two-phase to three-phase and if the two-phase side is balanced ($\mathcal{E}_{x2}=0$), the component $\mathcal{E}_{A2}$ will be zero if $m/\sqrt{3}=\frac{1}{2}$ or $m=\sqrt{3}/2$. Vice-versa if the three-phase side is balanced ($\mathcal{E}_{A2}=0$), $\mathcal{E}_{x2}$ will be zero if the same condition is satisfied.

147. The condition of perfect balance will usually exist only when the transformer is carrying **no load.** Assuming that the transformer *BR* is symmetrical about *D*, but that the ratio *m* of the other transformer may be in error, the positive and negative phase-sequence components of current for a symmetrical load having impedances Z_0 and Z_0' respectively to these components may be found when the following impedances are known:

$\dot{Z}_x$ measured between *A* and *D* with *PQ* short-circuited
$\dot{Z}_y$ measured between *B* and *C* with *RS* short-circuited
$\dot{Z}_z$ measured between *D* and *B* with *BC* short-circuited

The solution is

$$\left.\begin{aligned} I_{A1}=&\\ &\frac{1}{\dot{Z}_0}\left[\frac{3\left\{\dot{Z}_0\dot{Z}_0'+\dot{Z}_0\left(\dot{Z}_x+\dot{Z}_z+\frac{3}{4}\dot{Z}_y\right)\right\}\dot{E}_{A1}-3\dot{Z}_0\left(\dot{Z}_x+\dot{Z}_z-\frac{3}{4}\dot{Z}_y\right)\dot{E}_{A2}}{\dot{Z}_0\dot{Z}_0'+(\dot{Z}_0+\dot{Z}_0')\left(\dot{Z}_x+\dot{Z}_z+\frac{3}{4}\dot{Z}_y\right)+3\dot{Z}_y(\dot{Z}_x+\dot{Z}_z)}\right]\\ I_{A2}=&\\ &\frac{1}{\dot{Z}_0}\left[\frac{3\left\{\dot{Z}_0\dot{Z}_0'+\dot{Z}_0'\left(\dot{Z}_x+\dot{Z}_z+\frac{3}{4}\dot{Z}_y\right)\right\}\dot{E}_{A2}-3\dot{Z}_0'\left(\dot{Z}_x+\dot{Z}_z-\frac{3}{4}\dot{Z}_y\right)\dot{E}_{A1}}{\dot{Z}_0\dot{Z}_0'+(\dot{Z}_0+\dot{Z}_0')\left(\dot{Z}_x+\dot{Z}_z+\frac{3}{4}\dot{Z}_y\right)+3\dot{Z}_y(\dot{Z}_x+\dot{Z}_z)}\right] \end{aligned}\right\} \quad (51)$$

The expression in brackets in the solution for I_{A1} is the **positive phase sequence component** of the terminal e.m.f. under load; and that in the solution for I_{A2} is the **negative phase-sequence component** of the terminal e.m.f. If *m* has the correct value, namely $\sqrt{3}/2$ and the two-phase circuit is balanced, $\mathcal{E}_{A2}$ in the above expression becomes zero. If in addition to this

$$\dot{Z}_y=\frac{4}{3}(\dot{Z}_x+\dot{Z}_z) \quad (52)$$

I_{A2} will also be zero and the transformation will be symmetrical with respect to e.m.fs. between lines.

148. If a neutral point be provided for grounding which is correctly located for no load, it will shift as the load increases and the system will have a mean potential to ground given by the **zero phase-sequence component** of the e.m.f. to neutral and is given by

$$\dot{E}_{A0}=-\frac{2}{3}\dot{Z}_z(\dot{I}_{A1}+\dot{I}_{A2}) \quad (53)$$

149. When the load includes no rotating machinery Z_0 and Z_0' have the same value; but when the load consists of induction or synchronous motors or converters, Z_0' becomes relatively small compared to Z_0, and consequently dissymmetry in transformation may lead to excessive heating in rotating apparatus. In rotating apparatus Z_0' is a fixed quantity at a given speed, approximately equal to the locked impedance in the induction motor; Z_0 will depend on the load and in synchronous apparatus will vary with the excitation. It may in every case be expressed in the form $r_0+r_w+r_0+jx_0$, where $3I_{A1}^2r_w$ is the wasted work done against iron loss, windage, and friction, and a small amount of work required to overcome the negative torque due to I_{A2}. The total loss in the motor will then be

$$3\{I_{A1}^2(r_w+r_0)+I_{A2}^2r_0'\}$$

150. If the transformation is from three-phase to two-phase, E_{x1} and E_{x2} should be obtained in terms of $\mathcal{E}_{A1}$ and $\mathcal{E}_{A2}$ **the positive and negative phase-sequence components** of the three-phase impressed e.m.f. from equation 47, and if I_{x1} and I_{x2} are the corresponding symmetrical components of the two-phase system of currents and Z_0 and Z_0' the respective impedances to these components of a symmetrical two-phase load,

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$$\left.\begin{aligned} I_{A1} &= \frac{1}{\dot{Z}_0}\left[\frac{2\left\{\dot{Z}_0\dot{Z}_0' + \dot{Z}_0\left(\frac{\dot{Z}_x+\dot{Z}_s}{(m\rho)^2}+\frac{\dot{Z}_y}{\rho^2}\right)\right\}\dot{E}_{z1} - 2\dot{Z}_0\left(\frac{\dot{Z}_x+\dot{Z}_s}{(m\rho)^2}-\frac{\dot{Z}_y}{\rho^2}\right)\dot{E}_{z2}}{\dot{Z}_0\dot{Z}_0' + (\dot{Z}_0+\dot{Z}_0')\left(\frac{\dot{Z}_x+\dot{Z}_s}{(m\rho)^2}+\frac{\dot{Z}_y}{\rho^2}\right)+\frac{4\dot{Z}_y}{\rho^2}\left(\frac{\dot{Z}_x+\dot{Z}_s}{(m\rho)^2}\right)}\right] \\ I_{A2} &= \frac{1}{\dot{Z}_0}\left[\frac{2\left\{\dot{Z}_0\dot{Z}_0' + \dot{Z}_0'\left(\frac{\dot{Z}_x+\dot{Z}_s}{(m\rho)^2}+\frac{\dot{Z}_y}{\rho^2}\right)\right\}\dot{E}_{z2} - 2\dot{Z}_0'\left(\frac{\dot{Z}_x+\dot{Z}_s}{(m\rho)^2}-\frac{\dot{Z}_y}{\rho^2}\right)\dot{E}_{z1}}{\dot{Z}_0\dot{Z}_0' + (\dot{Z}_0+\dot{Z}_0')\left(\frac{\dot{Z}_x+\dot{Z}_s}{(m\rho)^2}+\frac{\dot{Z}_y}{\rho^2}\right)+\frac{4\dot{Z}_y}{\rho^2}\left(\frac{\dot{Z}_x+\dot{Z}_s}{(m\rho)^2}\right)}\right] \end{aligned}\right\} \quad (55)$$

The expressions in brackets are the **positive and negative phase-sequence components** of the terminal e.m.fs. on the two-phase side. If m has the correct value and the three-phase impressed e.m.f. is balanced, $\dot{E}_{z2}$ is zero. If in addition to this,

$$\dot{Z}_y = \frac{\dot{Z}_x+\dot{Z}_s}{m^2} \quad (56)$$

I_{A1} will also be zero. This is clearly seen to be the same condition as that given by Eq. 52. A stable neutral may be obtained on the two-phase side under all conditions.

151. If a corrective impedance is required to increase the value of $\dot{Z}_y$, its equivalent must be added on the two-phase side of transformer BR (Fig. 25), for if it were added to $\dot{Z}_y$ on the three-phase side it would have the effect of increasing $\dot{Z}_s$ also. With properly designed transformers the unbalance due to the impedances is trifling compared to that arising from other causes, but there are occasions when it becomes necessary to use transformers designed for other purposes having incorrect ratios and high values for $\dot{Z}_s$; it is then desirable to be able to determine the extent of unbalance due to these causes and if necessary correct them.

152. Two-phase to six-phase transformation. A double Scott connection is employed almost universally for this transformation; which is used solely for supplying six-phase power to **synchronous convertors** from two-phase supply systems. Two transformers are required having

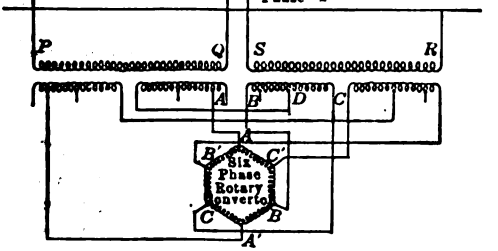


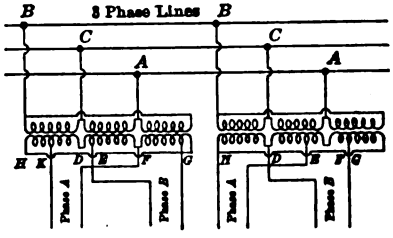
FIG. 26.—Two-phase to six-phase "Scott connection." Letters are arranged to show the relation to Scott connection two-phase to three-phase (FIG. 25).

their secondaries connected as shown in Fig. 26. The transformers are usually made alike so as to be interchangeable and the two secondaries are symmetrically arranged with respect to each other and the primary winding. The transformation may therefore be considered as a double two-

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phase to three-phase transformation and the unbalance calculated by Eq. 50. The impedance measurements for Z_x, Z_y and Z_z must be made with equal currents in both windings; this may be done conveniently by connecting the two parts in multiple when making the measurements and taking twice the values obtained in this way for the values of Z_x, Z_y and Z_z. In the case of the synchronous convertor the positive and negative phase-sequence impedances based on six-phase measurements or calculations should be used, the proper value being that obtained from the current in one lead and one-half the diametrical voltage. As the rating of a rotary convertor is very much affected by unbalance, it is important to see that the necessary conditions given in Par. 151 are fulfilled so as to minimise it.

153. Three-phase to two-phase transformation with three transformers. These methods of transformation offer some advantages in small installations where the cost of a spare unit is prohibitive, and it is desired to provide against the possibility of complete interruption of service due to the loss of one unit of a bank. They are also useful in installations where it is the intention at a later period to change over from two-phase to three-phase and it is desired to provide for standard three-phase connec-



Taylor Connection 3 Phase to 2 Phase with 3 Transformers
FIG. 27.

3 Phase to 2 Phase with 3 Transformers
FIG. 28.

FIGS. 27 and 28.—Three-phase connections using three transformers.

tions. That shown in Fig. 27 is known as the **Taylor connection.** Another of equal practicability is that shown in Fig. 28.

154. In all the preceding connections balanced currents in one system will produce balanced currents in the other system. There are numerous connections which will give balanced e.m.fs. but will not

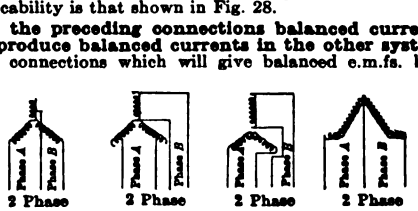


FIG. 29.—Three-phase to two-phase transformation systems.

transform a balanced load on one system to a balanced load on the other system. They are consequently of little importance. A few of the most important are illustrated in Fig. 29.

155. Three-phase to three-phase transformations. The delta-delta, the delta-star and the star-star connections are the most generally used; they are illustrated in Fig. 30. The star-delta and delta-delta con-

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nections may be used as step-up transformers for moderate voltages; the former has the advantage of providing a good grounding point in the low-voltage system which does not shift with unbalanced load, and has the further advantage of being free from third harmonic pulsation; the latter has the advantage of permitting operation in "V" in case of damage to one of the units. These connections are not suitable for transmission at very high voltage, but may be associated with other connections which provide means for properly grounding the high-voltage system; it is better, however, to avoid mixed systems of connections. The delta-star step-up and star-delta step-down connections are without question the best for high-voltage

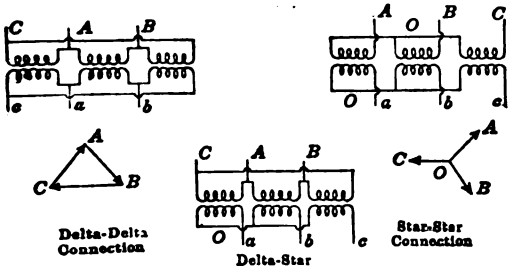


FIG. 30.—Standard three-phase to three-phase transformation systems.

transmission, as they are economical in cost and provide a stable neutral whereby the high-voltage system may be directly grounded, or grounded through resistance of such a value as to critically damp the system preventing thereby the possibility of oscillation. The star-star connection is discussed in the following paragraphs.

156. Star-star connection. To render this connection suitable for high-voltage transmission **delta-connected tertiary windings** must be provided. This arrangement of transformers is frequently used to interconnect two delta systems and provide a suitable neutral for grounding each of them. Sometimes auto-transformers are used for this purpose instead of two-coil transformers. In either case the delta-connected tertiary winding secures a two-fold purpose, as follows:

(a) **It permits a path for the flow of the third harmonic component of the magnetising current,** which in a star-connected bank of transformers is a zero-phase sequence system of currents and would, if the delta connection were absent, find a path through the neutral point and the capacity to ground of the transmission lines, and cause inductive disturbances.

(b) **In case of a ground on the system it permits enough current to flow to operate the protective apparatus.**

157. The effect of the tertiary delta in eliminating the flow of third harmonic currents through ground. (a) **First consider the neutral point isolated;** then the third harmonic component of the magnetising current can flow only in the tertiary delta, and therefore encounters the virtual impedance of this winding only. The limiting value for the third harmonic e.m.f. of neutral to ground is therefore the product of the third harmonic component of the magnetising current of the tertiary winding at normal induction, and its virtual impedance multiplied by the proper transformation ratio.

(b) **Secondly consider the tertiary delta open and the neutral point grounded.** Then the limiting value for the third harmonic current that will flow will depend upon the character of the external admittance and may be considerably greater than the third harmonic of the magnetising current under normal conditions.

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(c) **Lastly consider the neutral grounded with tertiary delta closed.** Then the action may be regarded as arising within the core in the form of a third harmonic e.m.f. causing current to flow both through the neutral to ground by way of the external admittance to ground and around the tertiary delta. The equivalent simple circuit is shown in Fig. 31 and consists of the equivalent circuit of a transformer (Par. 18) short-circuited at the end representing the tertiary and shunted on the grounded neutral side by an admittance representing the external admittance of the system to ground. The limiting value of the current that can flow in the joint circuit due to an internally set up third harmonic e.m.f. is equal to that of the third harmonic component of the magnetising current under normal conditions.

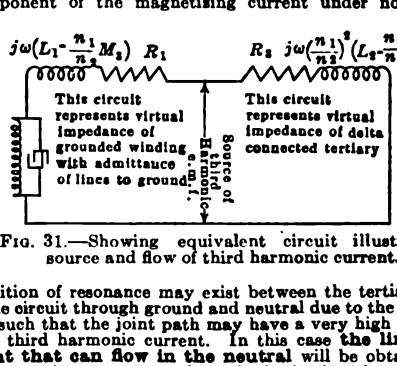


FIG. 31.—Showing equivalent circuit illustrating source and flow of third harmonic current.

But a condition of resonance may exist between the tertiary virtual reactance and the circuit through ground and neutral due to the external capacity to ground, such that the joint path may have a very high impedance to the flow of the third harmonic current. In this case **the limiting value of the current that can flow in the neutral** will be obtained by dividing the third harmonic component of e.m.f. obtained with tertiary delta open and neutral ungrounded by the sum of the virtual impedance of the winding to be grounded and the external impedance of one wire to ground.

(d) **Where two-coil transformers are used** and both windings are grounded there are three possible paths for the flow of the third harmonic magnetising current, namely, the delta tertiary and the two paths through the neutrals of each winding.

158. In star-star connected core-type transformers the third harmonic component of the e.m.f. becomes very small on account of the mutual inductance between phases, but it is advisable to provide such transformers with delta connected tertiaries.

159. The second function of the tertiary winding. It is important to be able to estimate the amount of current that will flow through ground in case one of the high-voltage lines becomes grounded. Take the simplest case and suppose a step-up star-star transformer is supplied by a generator. Let the ratio of transformation be ρ and let the positive and negative phase sequence impedance of the generator be Z_{A1} and Z_{A2}, respectively and let the internal generated voltage be E_{A1}. Let the high-voltage and low-voltage neutrals of the transformer both be grounded, but let that of the generator be free. Two impedance measurements will be required for the transformer; the ordinary short-circuit impedance measured on the high-voltage side with tertiary open, and the short-circuit impedance with tertiary closed, the low-voltage winding being open. Denote these by Z_T and Z_{T_0} respectively. At the point of short circuit we shall have the ground current in the high-voltage phases U, V, W respectively I, O and O, which resolved into its symmetrical components gives

$$I_{U0}=\frac{I}{3}; \qquad I_{U1}=\frac{I}{3}; \qquad I_{U2}=\frac{I}{3} \tag{5}$$

We obtain for the value of $I/3$

$$\frac{I}{3}=\frac{\rho E_{A1}}{Z_{T_0}+\rho^2(Z_{A1}+Z_{A2})+2Z_T} \tag{5}$$

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Find a value of $I'/3$ of $I/3$ for a tentative value E'_{A1} of E_{A1}. Then the e.m.f. across phase AB of the low-voltage winding will be

$$\dot{E}_c' = j\sqrt{3}\left\{a\dot{E}_{A1}' - \frac{\dot{I}'}{3}(\dot{Z}_{A1} - \dot{Z}_{A2}')\right\} \tag{59}$$

If E_c be the effective value at which the voltage across AB is held,

$$E_{A1} = \frac{E_c}{E_c'}E_{A1}' \tag{60}$$

and from this the true value of $I/3$ may be obtained. The currents in the high- and low-voltage windings of the transformer and in the tertiary winding

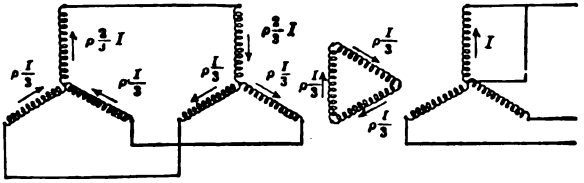
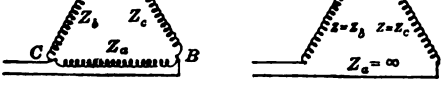


Fig. 32.—Showing distribution of current in star-star transformer with delta tertiary when line becomes grounded.

may then be calculated. They are shown in Fig. 32, the tertiary winding being assumed to have the same number of turns as the low-voltage winding. If the supply system instead of being a generator is a transmission line fed from generators through step-up delta-delta transformers, the impedance of the transmission system should be added to Z_{A1} and Z_{A2} after they have been multiplied by the proper transformation factor.

160. If the transformer is a three-phase core-type, the value of Z_{T_0} should be measured with all the high-voltage terminals connected together and the tertiary in delta, Z_{T_0} being one-third the value obtained in this manner.

161. Delta-delta connections are widely used for moderate transmission voltages. The case of unbalanced banks is of interest. If Z_a, Z_b and Z_c be the short-circuit impedance of the individual transformers



a — Delta connection with unlike transformers

b — "V" connection limit of Delta with unlike transformers.

Fig. 33.

of a bank, Fig. 33(*a*), let $\frac{Z_a+Z_b+Z_c}{9}$, $\frac{Z_a+\alpha Z_b+\alpha^2 Z_c}{9}$, and $\frac{Z_a+\alpha^2 Z_b+\alpha Z_c}{9}$

be represented by Z_{A0}, Z_{A1} and Z_{A2} respectively. If the impressed e.m.f. has components represented by $\dot{E}_{A1}$ and $\dot{E}_{A2}$, and if Z_0 and Z_0' be the impedances of a symmetrical star connected load to the positive and negative phase sequence currents, multiplied by the proper transformation factors, and if $\dot{I}_{A1}$ and $\dot{I}_{A2}$ are the component currents in the line,

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$$I_{A1} = \frac{\left(Z_0' + Z_{A0} - \frac{Z_{A1}Z_{A2}}{Z_{A0}}\right)E_{A1} + \left(Z_{A2} - \frac{Z_{A1}^2}{Z_{A0}}\right)E_{A2}}{\left(Z_0 + Z_{A0} - \frac{Z_{A1}Z_{A2}}{Z_{A0}}\right)\left(Z_0' + Z_{A0} - \frac{Z_{A1}Z_{A2}}{Z_{A0}}\right) - \left(Z_{A1} - \frac{Z_{A2}^2}{Z_{A0}}\right)\left(Z_{A2} - \frac{Z_{A1}^2}{Z_{A0}}\right)}$$

$$I_{A2} = \frac{\left(Z_0 + Z_{A0} - \frac{Z_{A1}Z_{A2}}{Z_{A0}}\right)E_{A2} + \left(Z_{A1} - \frac{Z_{A2}^2}{Z_{A0}}\right)E_{A1}}{\left(Z_0 + Z_{A0} - \frac{Z_{A1}Z_{A2}}{Z_{A0}}\right)\left(Z_0' + Z_{A0} - \frac{Z_{A1}Z_{A2}}{Z_{A0}}\right) - \left(Z_{A1} - \frac{Z_{A2}^2}{Z_{A0}}\right)\left(Z_{A2} - \frac{Z_{A1}^2}{Z_{A0}}\right)} \quad (6$$

The positive and negative phase-sequence components of the delta currents are obtained by the transformation in Eq. 48. The zero phase-sequence current I_{a0} is given by

$$I_{a0} = -\frac{jI_{A1}}{\sqrt{3}}\cdot\frac{Z_{A2}}{Z_{A0}} + j\frac{I_{A2}}{\sqrt{3}}\cdot\frac{Z_{A1}}{Z_{A0}} \quad (62)$$

162. The open-delta or "V" connection is an unsymmetrical connection which is used when one of a bank of a delta-connected transformers fails. It is sometimes used as a temporary connection with the intention of completing the delta when conditions of load warrant by the addition of a third transformer. Since the line currents pass through each transformer the rating of each should be 0.577 of the total kv-a. of the load. It may be considered as a limiting case of the unsymmetrical bank of delta-connected transformers. If both transformers are alike and have impedance Z (Fig. 33*b*) we shall have $Z_{A1} = Z_{A2} = Z_{A0} = Z/3$ and Eq. 61 when Z_{A0} is made indefinitely large reduces to

$$I_{A1} = \frac{\left(\frac{2}{3}Z + Z_0'\right)E_{A1} + \frac{1}{3}ZE_{A2}}{\left(\frac{2}{3}Z + Z_0\right)\left(\frac{2}{3}Z + Z_0'\right) - \frac{1}{9}Z^2}$$

$$I_{A2} = \frac{\left(\frac{2}{3}Z + Z_0\right)E_{A2} + \frac{1}{3}ZE_{A1}}{\left(\frac{2}{3}Z + Z_0\right)\left(\frac{2}{3}Z + Z_0'\right) - \frac{1}{9}Z^2} \quad (63)$$

If an impedance equal to Z, the impedance of one transformer, be placed in the line lead A on the primary side, the system will become symmetrical and we shall have

$$I_{A1} = \frac{E_{A1}}{Z + Z_0}$$

$$I_{A2} = \frac{E_{A2}}{Z + Z_0'} \quad (64$$

I_{A2} becoming zero when E_{A2} is zero.

163. Delta-star and star-delta connections. These are the best connections for use with **high-voltage transmission systems.** The same actions take place in the delta as in the delta-connected tertiary of the star-star connection (Par. **166**), but on account of the low virtual impedance of these windings there is no possibility of resonance, and therefore the neutral of the star may be grounded without introducing any trouble.

164. The solution for transformers of unequal impedance connected in a delta-star bank may be obtained from the solution for delta-delta connection (Eq. 61) by making $Z_{A1}Z_{A2}/Z_{A0}$, Z_{A1}^2/Z_{A0} and Z_{A2}^2/Z_{A0} all zero. The load impedances Z_0, Z_0' are the star impedances multiplied by the proper transformation constant. If ρ is the ratio of secondary to primary this transformation constant is $1/3\rho^2$. The zero phase sequence component of the currents in the primary delta is purely a magnetising current and is negligible. The terminal e.m.fs. of the secondary circuit are given by the symmetrical component e.m.fs. E_{U0}, E_{U1} and E_{U2} where

$$E_{U0} = \rho 3j(I_{A1}Z_{A2} - I_{A1}Z_{A1})$$

$$E_{U1} = \rho\sqrt{3}\,jI_{A1}Z_0$$

$$E_{U2} = -\rho\sqrt{3}\,jI_{A2}Z_0 \quad (65$$

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The zero phase sequence component is absent if the transformers are alike. The secondary positive and negative phase sequence components of current are

$$I_{U1}=\frac{I_{e1}}{\rho}=\frac{jI_{A1}}{\sqrt{3}\,\rho}$$
$$I_{U2}=\frac{I_{e2}}{\rho}=-\frac{jI_{A2}}{\sqrt{3}\,\rho} \qquad (66)$$

165. If the neutral point of the star secondary is solidly grounded, a ground on one line will be equivalent to a short-circuit across one pair of terminals of the generators through an impedance equal to that of one transformer measured across the secondary terminals plus the line and ground-return impedance up to the point of short-circuit multiplied by $1/p^2$.

166. The "T" connection is not extensively used. It has an advantage over the "V" connection in being more nearly symmetrical if the proper taps have been provided. As in the case of the "V" connection two transformers of a bank of delta-connected transformers, one of which has failed, may be connected in "T" and if the 10 per cent. taps be used for the teaser transformer the transformation will be more nearly symmetrical than if the "V" connection were used. Where "T" connected transformers are installed they may later be changed to delta with the addition of one more transformer and an increase in rating of the bank of

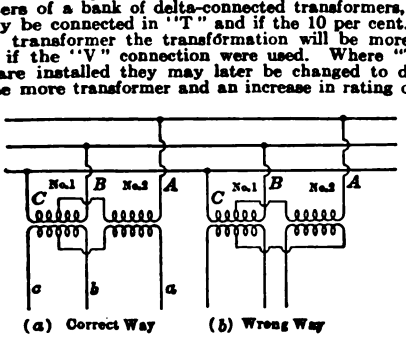


FIG. 34.—"T" Connected Transformers.

73 per cent. In the "T" connection (Fig. 34) the transformer AD known as the "teaser" transformer may be a duplicate of the main transformer so as to be interchangeable with it, and it may or may not be provided with an 86.6 per cent. taps. Its rated capacity will then be 15.5 per cent. more more than actually necessary. The main transformer operates at a power factor of 0.866, and therefore if the two transformers are duplicates their total rated capacity will be 15.5 per cent. greater than the capacity of the load in kv-a., or each transformer must have a rating of 0.577 of the kv-a. delivered. If the transformers are not interchangeable the teaser may be reduced to a rating of one-half the kv-a. delivered.

If Z_1 is the impedance of the teaser transformer with the secondary short-circuited, and if Z_2 is that of the main transformer through one-half of the secondary with the corresponding half of the secondary being short-circuited, and if Z_0 and Z_0' are the positive and negative phase-sequence impedances of the symmetrical star-connected load referred to the primary,

$$I_{A1}=\frac{\left(Z_0'+\frac{Z_1+2Z_2}{3}\right)E_{A1}-\frac{Z_1-Z_2}{3}E_{A2}}{\left(Z_0+\frac{Z_1+2Z_2}{3}\right)\left(Z_0'+\frac{Z_1+2Z_2}{3}\right)-\left(\frac{Z_1-Z_2}{3}\right)^2}$$
$$I_{A2}=\frac{\left(Z_0+\frac{Z_1+2Z_2}{3}\right)E_{A2}-\frac{Z_1-Z_2}{3}E_{A1}}{\left(Z_0+\frac{Z_1+2Z_2}{3}\right)\left(Z_0'+\frac{Z_1+2Z_2}{3}\right)-\left(\frac{Z_1-Z_2}{3}\right)^2} \qquad (67)$$

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In connecting transformers in "T" **care should be taken to keep the relative phase sequence of the windings the same,** other-wise the impedance of the main transformer may be excessively high and cause undue unbalance. Fig. 34 illustrates the right and the wrong way. If Z_1 and Z_2 are equal the system will transform symmetrically.

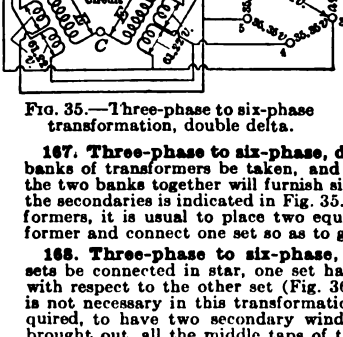


FIG. 35.—Three-phase to six-phase transformation, double delta.



FIG. 36.—Three-phase to six-phase transformation, double star.

167. Three-phase to six-phase, double delta. If two delta-connected banks of transformers be taken, and the polarity of one bank be reversed, the two banks together will furnish six-phase e.m.f. The relations between the secondaries is indicated in Fig. 35. Instead of using two banks of transformers, it is usual to place two equal secondary windings on each transformer and connect one set so as to give opposite polarity to the other set.

168. Three-phase to six-phase, diametrical. Similarly, if the two sets be connected in star, one set having its windings reversely connected with respect to the other set (Fig. 36), we shall have six-phase e.m.fs. It is not necessary in this transformation when the neutral connection is required, to have two secondary windings; instead a middle tap may be brought out, all the middle taps of the three transformers being connected together to form the neutral.

169. The interconnected-star connection shown in Fig. 37 is used in connection with direct-current three-wire distributing systems. This connection permits continuous current in the neutral wire to flow through the transformers without magnetizing them.

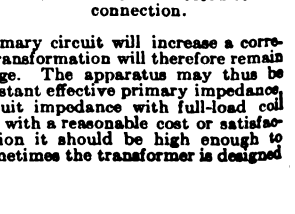


FIG. 37.—Interconnected star connection.

CONSTANT-CURRENT TRANSFORMERS

170. The constant-current transformer depends for its regulation on the force of repulsion between the primary and the secondary coils which carry currents that are in opposite time-phase. Referring to Fig. 35 and Fig. 4, as the load impedance decreases, the current will first increase, if the quantities $(L_1 - M)$ and $(L_2 - M)$ remain constant, but if the latter increases in the right proportion the current will remain constant. As the load impedance $r_0 + jx_0$ is decreased, the total reactance in the secondary circuit will decrease, and the short-circuit reactance of the primary circuit will increase a corresponding amount. The ratio of current transformation will therefore remain practically constant throughout the range. The apparatus may thus be considered as a device to maintain a constant effective primary impedance, independent of the load. The short-circuit impedance with full-load coil separation should be as low as consistent with a reasonable cost or satisfactory operation, but with no-load separation it should be high enough to limit the current to its normal value. Sometimes the transformer is designed

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with regulation to take care of the cutting out of a portion, only of the load impedance, in which case the short-circuit impedance voltage of the primary circuit for normal current will be less than the primary impressed voltage.

171. In the design of constant-current transformers for tungsten lamps, requiring a given total number of kv-a., a smaller transformer is required than that for arc lamps of the same kv-a. rating, on account of the low power-factor of the arc lamp. The design may be made along the same general lines as for power transformers, except that the short dimension of the coil space will be determined from the effective short-circuit impedance of the regulator with full-load coil separation, while the long dimension will be determined by the no-load short-circuit impedance required, and the length of the coils. The transformers are air cooled, the nature of the design affording free access of air to all working parts.

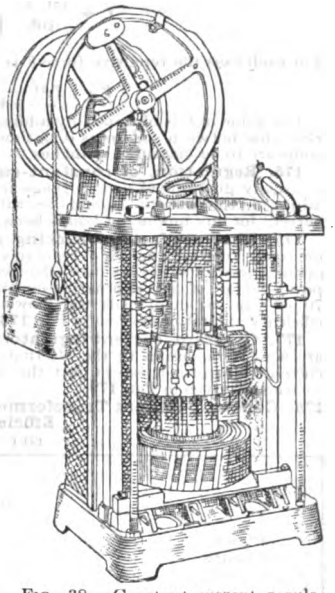


FIG. 38.—Constant-current regulator transformer.

172. Mechanical design and adjustments. The design usually comprises one stationary coil and a moving coil, the latter being the primary, with a suitable counterweight, as in Fig. 38. When both coils are movable they are usually arranged to counter-balance each other by means of lever arms or wheels. In both types, adjusting weights are required to obtain proper balance; adjustment also may be necessary in the relative lengths of lever arms at different positions. A dash pot should be provided to prevent pumping of the regulator and flickering of the lamps. Ten per cent. primary voltage tape above and below normal are sometimes provided.

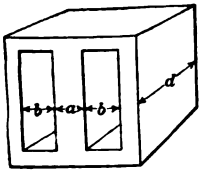


FIG. 39.—Magnetic circuit of constant current regulator.

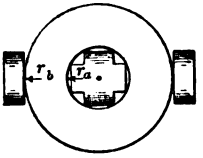


FIG. 40.—Cross-section of cruciform core of constant current regulator.

173. Types and characteristics. The one general type now in use, which experience has shown most efficient, consists of a shell-type magnetic circuit of rectangular or cruciform cross-section, with a movable coil system as described in Par. **172.**

174. Formulas for constant-current transformers. The formulas for the effective primary inductance and repulsive force are given below: the symbols refer to the dimensions shown in Fig. 39 and Fig. 40. The inductance for a rectangular-core regulator is

$$L = \frac{4\pi CN^2}{10^9}\left\{\frac{5.08d}{b} + 129\left(\frac{1}{\pi + \frac{2b}{a+b}}\right)^2\right\} \quad \text{(henrys)} \qquad (68)$$

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The inductance for a cruciform-core regulator is

$$L = \frac{4\pi CN^2}{10^9}\left(\frac{7.6}{0.23 + \log \frac{r_a}{r_b}}\right) \quad \text{(henrys)} \quad (69)$$

For each case the repulsive force F is

$$F = \tfrac{1}{2} I_1^2\left(\frac{100L}{4.45 \times 2.54 \times C}\right) \quad \text{(pounds)} \quad (70)$$

The value of C is obtained by adding to the coil separation the insulation clearance between coils plus 0.45 times the length of each coil. All dimensions are to be measured in inches.

175. Regulation, of constant-current transformers for arc-lighting is usually guaranteed over a range from full load to no load. If properly adjusted, the current should be within 0.1 amp. of the normal value of current for any number of lamps between full load and no load.

176. The satisfactory working of alternating-current arc lamps demands a certain amount of reactance in the lamp circuit. This is provided in the transformer by its own effective reactance. The full-load operating power-factor of an alternating-current arc-lamp system seldom excells 70 per cent.; at small loads the power-factor is very much less. A table of efficiency and rating is given in Par. **178.**

177. Constant-current regulators for series tungsten lamp lighting are similar in design to the alternating-current series arc lamp constant-current transformer, except that the dashpot is omitted. Ratings and efficiencies are given in Par. **179.**

178. Constant-current Transformers for Arc-Lighting; Ratings and Efficiencies

60 Cycles

	Secondary amp.			Full-load efficiency
	6.6	7.5	10.0	
No. of lamps	6	5	6	90.2
No. of lamps	13	11	12	92.5
No. of lamps	20	17	18	92.7
No. of lamps	27	24	25	93.3
No. of lamps	38	34	35	93.9
No. of lamps	55	48	50	94.6
No. of lamps	83	72	75	95.3
No. of lamps	110	96	100	95.7

179. Ratings, Power-factors and Efficiencies of Constant-Current Transformers for Operating Series Tungsten Lamps

60 Cycles

Kw.	Efficiency per cent.				Primary power-factor per cent			
	¼ load	½ load	¾ load	full load	¼ load	½ load	¾ load	full load
4.0	73.7	86.5	90.5	91.7	22.9	50.6	75.6	83.7
8.0	78.7	89.2	92.5	93.65	23.1	51.8	77.4	84.9
12.0	79.7	89.8	93.0	93.8	23.3	52.3	78.1	85.2
17.0	81.2	90.7	93.5	94.5	23.6	52.5	78.5	85.4
24.0	82.8	91.6	94.2	95.0	23.8	52.7	79.0	85.6
25 Cycles								
4.75	71.9	86.0	90.3	91.0	24.5	51.2	76.8	84.2
7.0	74.5	87.6	91.3	92.0	24.9	52.7	78.3	85.7
10.0	76.4	88.7	92.0	92.3	25.3	53.6	79.8	87.0
14.0	77.0	89.1	92.5	93.1	25.6	54.3	80.7	88.1
20.0	79.1	90.3	93.3	94.0	25.8	54.8	81.3	88.6
28.0	82.6	92.0	94.5	96.0	25.9	55.1	81.4	88.7

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The above values of performance are based on constant-current transformers designed to operate on a 2,200-volt circuit; the number of lamps comprising the secondary load will depend upon their operating current and voltage.

AUTO-TRANSFORMERS

180. General principles. The auto-transformer is nothing more than a transformer so connected that part of the load current is supplied by the primary current, and part by the secondary current. The relative amount supplied by each will depend upon the ratio of transformation. If the ratio of transformation is large, the current in the secondary will be large compared with that in the primary, and the proportion of the load current contributed by the primary current will be small; on the other hand, if the ratio of transformation approaches unity the primary current will be large compared with the secondary current, and therefore the primary current will supply the greater portion of the load. Fig. 41 illustrates the connections of a transformer for use as an auto-transformer, and gives also a physical conception of the current relations in the latter. The primary voltage is the difference between the voltage of the supply circuit and that of the secondary circuit. The load current is supplied from the primary and the secondary in approximately inverse proportion to the respective number of turns in their windings. Therefore, the lower the ratio of transformation, the smaller will be the transformer required to deliver a given load, and the more efficient will be the transformation. The method of connection may be modified from that shown in Fig. 41, but the principle is unchanged. As the load on the secondary is increased the primary voltage becomes greater, so that the regulation of an auto-transformer is very much better than when used as a simple transformer.

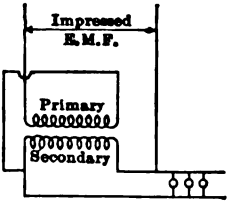


FIG. 41.—Transformer shown connected as an auto-transformer.

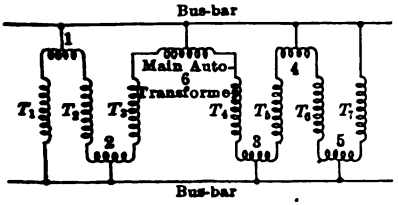


FIG. 42.—Use of auto-transformers for paralleling transformers.

181. Types and characteristics. Auto-transformers may be used for every purpose for which transformers are used, but there is little to be gained by using them for large ratios of transformation, and on high-voltage work their use requires a grounded system for the sake of safety in operation.

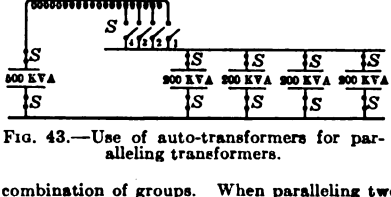
182. Auto-transformers for power purposes may be used instead of transformers to step-up or step-down the voltage of a grounded transmission line. Such an arrangement is found very convenient when supplying power to a grounded system from a grounded supply circuit. A good example of the use of auto-transformers for power purposes is afforded by the New York, New Haven and Hartford Railroad system, in which the 11,000-volt trolley circuit is supplied through auto-transformers at each section from the 22,000 volt-feeder circuits. Auto-transformers may also be used as a means of interlinking two systems of different voltages; the three-phase auto-transformer is commonly used for this purpose.

183. Auto-transformers or balance coils are often employed to obtain the middle wire, or neutral wire, of a three-wire alternating-current system. The size of balance coil used is ordinarily one that will take care of 25 per cent. unbalancing of the system.

184. Auto-transformers or balance coils for three-wire direct-current systems. The connection shown in Fig. 23 of Sec. 9 is sometimes used to obtain the neutral of a three-wire direct-current system.

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185. Auto-transformers for producing a proper division of the load between transformers operating in parallel. There are several ways in which auto-transformers may be used for this purpose; one of these, by which a group of any number of transformers of one design may be connected so as to operate in multiple with a group of any number of transformers of another design, is illustrated by Fig. 42. The illustration shows only single-phase groups, but polyphase groups may be paralleled in a similar manner.


M
S
S
S

transformer. In each case OE is the secondary e.m.f. at 100 per cent. power-factor and OG is the e.m.f. across the remaining portion of the winding. The triangle HGK is equal to BEF. The vector diagrams, Fig. 44 and Fig. 45, show the regulation for a load of 100 per cent. power-factor; the loci for any load of any power-factor may be obtained by following the construction shown in Fig. 6, described under "General Theory," Par. **23**.

187. The cost of an auto-transformer designed to deliver a given amount of power P, depends upon the ratio of transformation. The actual rate at which energy is transformed electromagnetically in the auto-transformer, is the true criterion of its cost; this rating may be conveniently referred to as the **equivalent transformer rating**, though it should be kept in mind that in the auto-transformer the insulation stresses may be different from those that occur in the transformer. If m be the ratio of the low-tension e.m.f. to the high-tension e.m.f. of the auto-transformer at no load, the equivalent transformer rating will be $(1-m)P$, where P is the auto-transformer rating. If $m=\frac{1}{2}$, the transformer rating of the auto-transformer is one-half its auto-transformer rating. If m be very small, the two ratings approach equality; if m be larger, the transformer rating is very small compared with the auto-transformer rating. The cost of the auto-transformer may thus be expressed in terms of a two-winding transformer with certain conditions of insulation stress to be considered. Since auto-transformers are most generally used on low-voltage circuits, the effect of the difference in insulation stress is usually negligible.

188. Induction starters are auto-transformers connected for operation on polyphase circuits, to reduce the voltage applied to an induction motor at starting. Usually a number of starting-points are provided, so that the same design may be used for different starting conditions.

INSTRUMENT TRANSFORMERS

189. Voltage (shunt-type) transformers are used for many classes of work, such as operating relays for voltage regulation and protection, operating recording instruments, power-factor meters, and switchboard instruments, including voltmeters and wattmeters. For accurate work a potential transformer should carry the load of one instrument only, and should be compensated for this load.

190. In the design of voltage (shunt-type) transformers it is important to keep the weight of iron and the effective impedance as low as possible; therefore the insulating material used must be highly efficient as an insulator, and the coils must be so subdivided, wound, and insulated as to occupy the minimum amount of space. The induction must be fairly low, so as to avoid distortion of wave form due to the exciting current.

191. Compensation for the effect of the load current and the exciting current may be calculated from the equivalent circuit as discussed in Par. **19**, under "General Theory." No definite rules can be laid; the best guide is a comparison between calculated values and test results.

192. Voltage transformers are manufactured to operate on all voltages, up to 100,000 volts. For very high voltages the design of a reliable transformer of low cost becomes exceedingly difficult; the cost of the terminals alone is a very large item.

193. Current (series type) transformers. It has been shown that in such transformers the effect of wave-form distortion of the secondary current on the accuracy of measurements is so small as to be undetectable, even with the most accurate instruments available. It follows that in considering any particular load the wave form of the secondary current may be assumed to be a sine-wave and the equivalent sine-wave value of the exciting current may be taken. It will be found convenient in practical work to consider the ratio as unity, and the primary current reversed in time phase so as to be nearly in phase with, instead of being nearly in opposition to, the secondary current, it being of course understood that the phase of one of them must be reversed in a transformer. Then, referring to Fig. 4 under "General Theory" (Par. **19** to Par. **22**), we find that the induced voltage in the secondary circuit under load of impedance $Z_0 = R_0 + j\omega L_0$ is

$$\dot{I}_2\left[R_2 + R_0 + j\left\{(\omega[L_2 - M] + \omega L_0\right\}\right] \qquad (72)$$

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The mean induction in the core will depend on this e.m.f. and may be found by means of Eq. 4. Let the angle of lag of the exciting current behind the induced e.m.f. be α and let its value considered with reference to the secondary winding be I_m; then if the angle of lead of the induced e.m.f. over I_2 be θ, determined by the formula,

$$\tan\theta = \frac{\omega(L_2 - M) + \omega L_0}{R_2 + R_0} \tag{73}$$

we shall have

$$\bar{I}_1 = I_2\left[\sqrt{1 + \left(\frac{I_m}{I_2}\right)^2 + 2\frac{I_m}{I_2}\cos(\theta - \alpha)}\right]\epsilon^{j\theta_1} \tag{74}$$

where θ and α are already defined, and the value of θ_1 is found from the formula

$$\tan\theta_1 = \frac{\frac{I_m}{I_2}\sin(\theta - \alpha)}{1 + \frac{I_m}{I_2}\cos(\theta - \alpha)} \tag{75}$$

The quantity under the radical in Eq. 74 is the factor by which the ratio of turns must be multiplied in order to get the ratio of transformation, and θ_1 is the lay of the primary current over the secondary current.

194. The important factors in the design of series (current) transformers are the load impedance and the effective secondary impedance for these together determine the mean induction in the iron for a given secondary current. These factors being fixed the excellence of the design will depend on the quality of the iron and the care taken in building which should be such as to make I_m as small as possible. Care should be taken in the mechanical design to avoid eddy currents in the end frames, and in the electrical design that in the endeavor to make the induction low by using a large number of turns this purpose is not defeated by the large increase in secondary reactance produced thereby.

195. The effect of these factors and of different qualities of iron may be studied by means of curves of ratio and phase displacement, such as that shown in Fig. 46 which was made by a method similar to those recommended by Crawford and Sharp, Agnew and others (see Sec. 3).

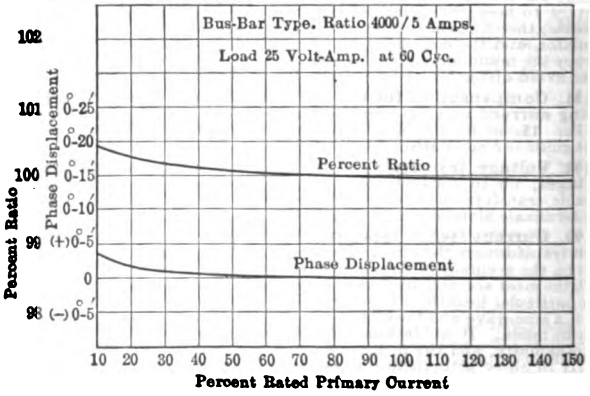


FIG. 46.—Calibration curve of a standard bus-bar type series transformer.

196. Current (series) transformers for high-voltage circuits are generally costly on account of the necessity of insulating them heavily and if they are oil-immersed they require in addition a high-voltage terminal.

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A new design has been developed for high voltages which is less costly. It consists of a core which is wound with the secondary winding, while the primary winding is wound through a condenser lead which passes through the opening of the core.

197. Correction factors for power measurements. Errors introduced in measurements made with the use of series (current) and shunt (potential) transformers are usually negligible, if the power-factor of the load measured is high. On low power-factors the results will be inaccurate to an appreciable degree and the calibration curves of the transformers should be used in order to make the necessary corrections. If the power-factor of the load be cos α and the angle of lead of the secondary current of the series (current) transformer be θ_1 and the angle of lead of the secondary e.m.f. of the shunt (potential) transformer be θ_2, and if ρ_1 and ρ_2 are the corrections to be applied to their name-plate or nominal ratios as indicated on the correction curve (Fig. 46), and further if E_2 and I_3 are the observed values of the secondary e.m.f. of the shunt (potential) transformer and the secondary current of the series (current) transformer, respectively, then

$$\cos(\alpha - \theta_1 + \theta_2) = \frac{\text{wattmeter reading}}{E_2 I_3} \qquad (76)$$

The correct value for the power measured will then be obtained by multiplying the observed reading by the factor

$$\left[\frac{\cos\alpha}{\cos(\alpha-\theta_1+\theta_2)}\right]\rho_1\rho_2 \text{ multiplied by (product of nominal ratios)}$$

198. Standard current (series) transformers are designed to give a current of 5 amp. in the secondary winding with full-load current in the primary winding, and a load of 25 volt-amp. They are made for use on circuits from 2,200 volts up to 20,000 volts, air-cooled, and for primary currents of 5, 10, 15, 20, 30, 40, 50, 60, 75, 80, 100, 120, 200, 300 and 400 amp. Transformers designed to slip over a stud or cable which constitutes a one-turn winding, are made for primary currents from 600 amp. up to 3,000 amp. Series (current) transformers for higher voltages than 20,000 volts are usually oil-insulated.

199. All instrument transformers should have their secondary windings grounded, because a high potential may be induced in the secondary winding depending on the mean potential of the primary winding to ground and the ratio between the electrostatic capacity of the secondary winding to ground, and the electrostatic between primary and secondary windings. In addition to this in the case of current transformers precaution should be taken to see that the *secondary winding is short-circuited before an instrument is removed*, otherwise an excessive e.m.f. will be induced in the secondary winding due to the line current now becoming the magnetizing current of the transformer. This is true of all series (current) transformers, but the e.m.f. becomes particularly high in transformers designed for a high degree of accuracy, and in bus-bar type transformers for 1,000 amp. and above.

TRANSFORMERS FOR MISCELLANEOUS USES

200. Track transformers for operating signals are small transformers similar in design to those used for sign lighting, hereafter described. The secondaries of the transformer are connected across the two rails of a track while the primaries are supplied from 110 volt feeders which are in turn supplied by small step-down transformers similar to standard lighting transformers from 60 cycles or 25 cycles 2,200- or 6,600-volt transmission lines.

201. A line-drop compensator is a device for obtaining with a voltmeter located in the generating or substation the voltage at the end of a line, or at some predetermined point, and consists essentially of a reactance and a resistance in series, which may be varied by means of taps. A current proportional to the line current is circulated through them by means of a series-type (current) transformer, and the secondary of a shunt-type (potential) transformer is connected to the proper point of one of them by means of a dial; the voltmeter or potential relay is connected between the remaining terminal of the shunt-type transformer, and the proper point of the other element of the compensation, by means of a dial. With a proper choice of current transformer and with proper connections and adjustment

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of the dials the voltmeter or potential relay will indicate the voltage at the desired point of the feeder or line for any load.

202. Theory of line-drop compensators. Refer to Fig. 6 (under "General Theory"). The voltage at the station is represented by the secondary open-circuit voltage, and the voltage at the end of the line or centre of distribution is represented by the secondary full-load voltage; the reactance drop and the ohmic drop of the compensator are represented by the secondary short-circuit reactance drop and resistance drop, respectively.

203. In order to obtain the highest accuracy with line-drop compensators, it is necessary that the voltmeter operate on a small current compared with that passing through the compensator. Compensators for use with potential regulators, should be designed for larger currents than those for use with indicating instruments.

204. Compensating transformers for neutralizing inductive disturbances in telephone and telegraph lines. Where telephone or telegraph circuits parallel an alternating-current traction system, high voltages may be induced in them due to electromagnetic induction from the railway system. To overcome this trouble, a number of extra pairs of wires are placed among the other telephone wires so that their mutual inductance to the railway circuits is the same as those of the regular telegraph or telephone wires. These extra wires are grounded at various points, and connected to the primary windings of a special transformer, so that the e.m.fs. induced in them magnetize the transformer in the same direction. The telephone or telegraph wires are then connected to secondary coils of this transformer, so that the induced e.m.f. of the transformer opposes and neutralises the induced e.m.f. due to the railway system. Since the two wires of any pair encircle the core in the same direction, the secondary windings are practically non-inductive, as far as the telephone currents are concerned. The transformers are usually of the core-type construction and differ from ordinary transformers only in the large number of secondary coils and the manner in which they are wound so as to obtain freedom from cross talk.*

205. Insulating transformers for telephone lines are designed to protect both the telephone and the user from high voltages, due either to induction or accidental contact with a high-tension line. This device consists of a shunt transformer provided with a condenser across the primary terminals, the purpose of the condenser being to supply the greater portion of the magnetizing current of the transformer under normal operation. The secondary terminals are connected to the telephone in the usual way. Such transformers are usually built to stand a 25,000-volt test, for 1 min., between the windings, and between windings and case. A lightning arrester and special fuses are generally provided for the primary circuit. The secondary may be grounded if desired, or an insulated stool provided for the user to stand upon.

206. Extra-high-voltage testing transformers. Test voltages as high as 375,000 volts above ground potential are becoming common, such a test voltage requires a testing transformer equivalent in insulation strength to one designed for 750,000 volts with the middle-point grounded. In the testing of insulators an artificial ground is commonly used for the higher voltages. This method of testing is economical in the respect that it requires a transformer insulated for only one-half the potential necessary when test specifications require that one terminal be grounded; but it is open to doubt whether tests made in this manner are as exacting as those made with one side of the circuit grounded. Testing transformers may now be obtained suitable for intermittent testing up to 600,000 volts with one terminal grounded, and up to 750,000 volts with the middle-point grounded. One testing transformer in present service has been tested up to 720,000 volts, effective (by spark-gap measurement), with one end grounded; another has been tested momentarily up to 900,000 volts, effective (by spark gap), with the middle-point grounded. The voltage impressed on the primary is raised either by cutting out resistance as in the potentiometer method of controll or by employing a dial and a separate regulator transformer.

207. Bell-ringing transformers. The bell-ringing transformer, connected to a 110-volt, 60-cycle, lighting circuit, produces at its secondary

*See article in *Electric Journal* for October, 1914, by Shaw.

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terminals a voltage suitable for operating door-bells, buzzers, annunciators, miniature incandescent lamps, or for any purpose for which dry or wet-cell batteries are used. The transformer has the advantage over batteries that it requires no attention after it has been installed, and there is no further expenditure, since its life is probably indefinitely long; and, furthermore, the annoyance of having bells out of order due to battery failures is done away with. The amount of energy consumed at no load is very small, being about 1 watt. Voltages of 16 or 24 volts are obtained.

208. Transformer equipments for thawing water pipes by electricity. These equipments consist of a transformer having high reactance, or a transformer and an external reactance combined. When in operation, the high-tension leads are connected to the main-line feeders. The secondary leads may be connected to any convenient points in the piping system, so that the frozen portion is included in the circuit. The transformers are generally air cooled and portable.

209. Sign-lighting transformers. The standard practice in lighting electric signs is to use 10-volt tungsten lamps of about 4 c-p., which have a watt consumption per candle-power of only a little over one-fourth that of carbon-filament lamps of the same candle-power, and to operate these lamps in multiple, using a step-down transformer by which the pressure of the 110-volt or 220-volt supply circuit is reduced to a suitable value. These transformers are designed for use on 60 cycles, at voltages of 240, 220, or 200 volts, or at 120, 110, or 100 volts, and will deliver their full rated load at either 10 or 20 volts. The ratings and efficiencies of these transformers are as follows, in Par. **210**.

210. Table of Ratings, Efficiencies and Weights of Sign-lighting Transformers

Rating in watts	Efficiency				Wt. lb.
	¼ load	½ load	¾ load	Full load	
160	85.3	90.5	91.5	91.5	17.0
250	84.1	90.2	92.0	92.6	28.0
375	87.1	91.9	93.1	93.3	31.0
500	87.8	92.4	93.5	93.7	34.0
1,000	91.3	94.4	95.1	95.0	70.0
2,000	91.5	95.0	95.9	96.2	86.5

211. Transformers for operating series incandescent lamp from series arc-lamp circuits are essentially series-type (current) transformers of suitable dimensions and windings for the service required. They are designed to transform the current from the value in the series arc-lamp circuit to a value suitable for series tungsten lamps. Besides giving good regulation, a transformer of this kind must be arranged so that in event of the secondary becoming open-circuited while the primary current is at normal value, the rise in voltage will not be excessive. These characteristics are secured by contracting the section of the core at several points, so that the iron becomes saturated at full-load primary current and thus limits the secondary voltage to a value approximately 150 per cent. of its normal full-load value.*

TRANSFORMER TESTING

212. Transformer testing may be conveniently classified as follows:

(a) Shop tests made during process of manufacture for the purpose of discovering any gross defects in the winding of coils and in the insulation of the completed transformer. See Par. **213**.

(b) Specification tests to determine whether the factory has correctly followed the engineer's specifications. See Par. **214** and **215**.

(c) Measurements of losses and determination of performance and regulation. These must meet the manufacturer's guarantees. Par. **216** to **218**.

(d) Heat tests to determine running temperature. The temperature

* *General Electric Review*, June, 1911, p. 293.

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rises under certain specified conditions must meet the guaranteed values, Par. **219** to **223**.

(e) Insulation tests. These comprise the overpotential test which is made for the purpose of exposing any defect or injury in the insulation between turns, between layers, and between coils; the disruptive test for determining whether the insulation between the primary and the secondary windings and between these two windings and ground is sufficiently strong. Par. **224** to **227**.

(f) Tests on instrument transformers; calibration.

213. Shop tests. In the case of large power transformers these tests are sometimes omitted, but in their stead each coil is very carefully inspected during the course of winding and insulating. The tests to determine any defects in winding are made by placing each coil on a core which is furnished with a removable yoke, and inducing in each turn of the coil a specified e.m.f. A test to determine whether the insulation is intact after the coils are assembled and the iron built in, is made by subjecting the insulation between the primary and the secondary windings, and between each of these windings and ground, to a test of several thousand volts. The transformer is then ready for the testing department.

214. Tests to determine whether the transformer is correctly wound and assembled. The first test to make is the **ratio test.** This determines whether the transformer has been wound correctly and the leads and tap brought out in the right places. The methods used in making this test will depend upon the transformer to be tested. Large power transformers are tested for ratio by having a fraction of the normal voltage impressed on a winding while the voltage between taps is measured by means of a voltmeter, and the ratio of the tap voltage to the total is thus obtained. The ratio of the primary voltage to the secondary voltage is obtained in the same manner. Small transformers for lighting and small power service may be tested by balancing against a standard of known ratio. The same method applies to shunt-type (potential) transformers for instruments.

215. Polarity test. In power transformers this test follows the ratio test, and is made by connecting two adjacent primary and secondary

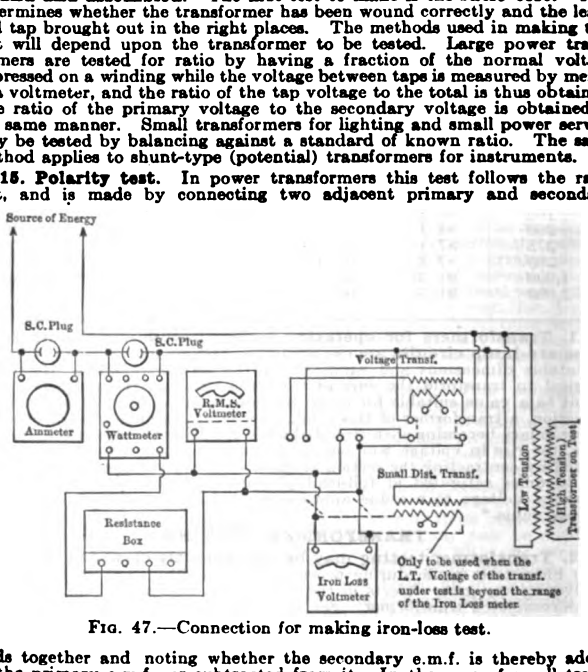


FIG. 47.—Connection for making iron-loss test.

leads together and noting whether the secondary e.m.f. is thereby added to the primary e.m.f., or subtracted from it. In the case of small transformers, the ratios of which are tested by comparison with a standard, the polarity is given at once by reference to that of the standard. Thus the apparatus for testing may be so arranged that if the polarity of the trans-

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former to be tested is wrong, a red pilot lamp becomes energised. This method of determining polarity is characteristic of all balance methods applied to alternating-current work, such as, for instance, the shunt-resistance method of testing the ratio and the phase displacement of series-type (current) transformers.

216. Measurements of losses comprise those for core-loss, and those for copper-loss and impedance volts. The core-loss consists of both hysteresis and eddy-current losses in the iron. Since the "flux-linkages" are the time integral of the induced e.m.f., and since all commercial e.m.f. wave-forms contain the odd harmonics only, the maximum value of B will be determined by the average value of E. And therefore the hysteresis loss will depend, not on the root-mean-square value of E, but on its average value. The eddy-current loss, on the other hand, will depend on the root-mean-square value of E. Hence the core-loss, to be measured accurately, must either be obtained on a circuit having an e.m.f. wave, whose average value and root-mean-square value have a specified ratio (the standard wave is sine-wave and the standard ratio of root-mean-square to average value is 1.11), or else compensation must be made for any deviation from this ratio by some device which indicates how much to raise or lower the voltage to obtain the correct loss. It is essential in the former case that the wave form at the terminals of the transformer, after correction has been made for wave distortion due to voltage, regulating devices, etc., shall be such that this ratio is equal to 1.11. The second method may be used with the aid of an **"iron-loss voltmeter"** (Sec. 3). Fig. 47 shows the connections used for measuring iron-loss. When the iron-loss voltmeter is used it should be connected in circuit with the root-mean-square voltmeter: both readings should be noted and correction made for the shunt loss of the wattmeter from the readings of the root-mean-square voltmeter. Strictly speaking, the loss should be taken with both voltmeters in circuit and corrections made for their losses also. The iron-loss voltmeter is provided with a scale by which its loss may be read directly.

217. In measuring the core-loss care should be taken that when a portion, only, of the winding of the transformer is used it is so situated that

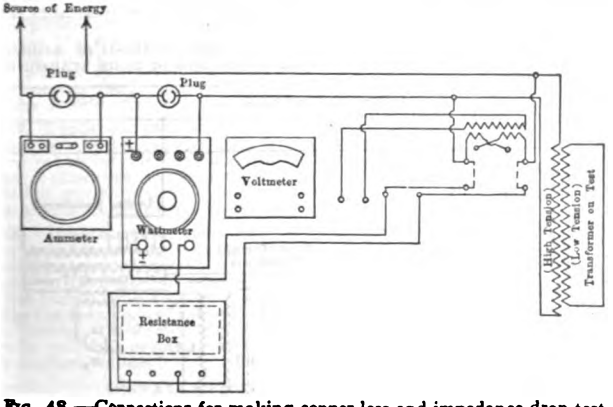


FIG. 48.—Connections for making copper-loss and impedance-drop test.

the magnetic leakage is practically the same as under normal open-circuit conditions. In general it is better to sacrifice a little in convenience and use the whole winding, than run the chance of error by using a portion of the winding. The value of impressed voltage used when the measurement is made on the secondary side should be the rated voltage plus the secondary IR drop. The **equivalent sine-wave exciting current** is obtained by

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the ammeter reading, and the true-watts component is obtained by dividing the observed core-loss by the value of rated secondary voltage plus the secondary IR drop.

218. Copper-loss and impedance volts. This measurement is made by short-circuiting one winding (properly it should be the primary winding) and circulating rated full-load current in the other, observing the loss in watts and the impressed voltage. The connections for the test should be made as shown in Fig. 48. The current should be adjusted with the voltmeter and the wattmeter shunt winding disconnected. The wattmeter may then be read first, followed by the voltmeter. If the exciting current of the transformer is high, a correction, obtained from Eq. 11, Par. **24**, must be added to the copper-loss measured as above. The copper-loss so obtained will be the true copper-loss of the transformer and includes the eddy-current loss in the conductors. By dividing the copper-loss by the rated output, the effective IR drop, expressed as a fraction of the rated voltage, will be obtained. Divide the observed voltage by the rated voltage, and the effective impedance-drop, expressed as a fraction of the rated voltage, will be obtained: the effective reactance drop, expressed as a fraction of the rated voltage, may then be obtained by taking the square root of the difference of the squares of these two quantities. Efficiencies and regulation may then be computed from these results by the usual formulas, which are given under "General Theory," Par. **24** to Par. **26**.

219. Tests for efficiency of cooling include the measurement of temperature rise above the cooling medium at various loads. Resistance measurements are also included, because they are necessary to determine the rise in temperature of the copper.

220. Resistance measurements may be made with a Wheatstone or a Kelvin bridge of the proper range. The conditions for measuring the cold resistance should be carefully prepared, so that the apparatus whose resistance is under determination will be at the temperature of the surrounding air. If the temperature of the room fluctuates, it is recommended that an idle unit be employed, of the same design as those on test. The resistance of the winding of the idle transformer may then be used as a basis from which to measure the temperature, by increase of resistance of the loaded transformer.

221. Methods of loading. There are various methods of artificially loading transformers. The best method, where two or more transformers

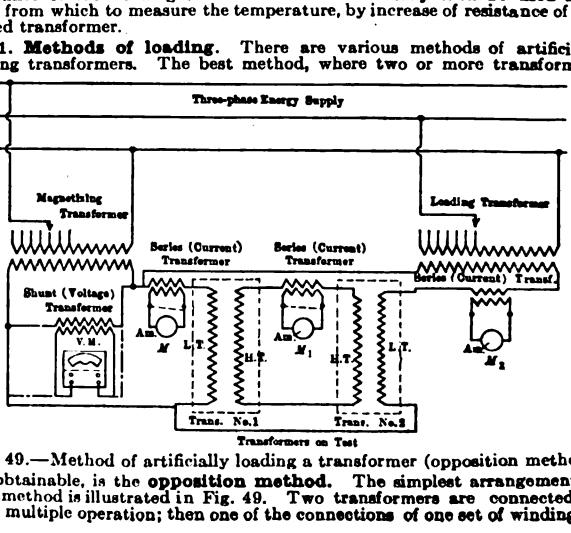


FIG. 49.—Method of artificially loading a transformer (opposition method).

are obtainable, is the **opposition method.** The simplest arrangement of this method is illustrated in Fig. 49. Two transformers are connected as if for multiple operation; then one of the connections of one set of windings is

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opened and full-load current is circulated in the circuit from an external source of energy. Either pair of windings is then excited from a suitable source at proper voltage and frequency. It is preferable that the time-phase relations of the exciting e.m.f., and the current-circulating e.m.f., should be capable of variation, so that the conditions of load may be varied to suit different requirements.

222. Measurements of temperature. After steady conditions have been reached, as indicated by thermometers placed at various points in the windings, preparations should be made for taking the **hot resistance.** To insure prompt measurement, the instruments should be set before-hand for the expected values, so that a quick adjustment may be made.

223. In making the heat test both wattmeters and ammeters may be used. The wattmeters may be arranged to read the total core-loss, the total copper-loss, and the power input or output. The power-factor of the load may be obtained and adjusted.

224. Insulation tests include **overpotential tests** for the purpose of determining whether the insulation between turns and coils is intact; and **disruptive tests** to determine the condition of insulation between primary and secondary windings and between these windings and ground. Sometimes, also, the **insulation resistance** between primary and secondary windings is measured.

225. Overpotential test. For large transformers an overpotential of double the rated low-tension voltage is usually applied for 5 min. to the low-tension terminals. It is desirable when making this test on high-voltage transformers to disconnect the high-voltage winding so as to reduce the voltage. In small transformers an overpotential of five times rated voltage at 500 cycles may be used. The overpotential test should be made while the transformer is hot.

226. Disruptive test. In making this test on power transformers the low-tension winding is connected to the iron and to ground, and the primary winding is connected to one end of a testing transformer, the other end of which is grounded. A sphere spark-gap should always be used, with tests above 50,000 volts, for measuring the voltage, as a rise in voltage is likely to occur in the testing transformer. The usual test is from two to two and one-half times line voltage. The Standards Committee of the A. I. E. E. give definite recommendations in regard to the tests to employ, and it is customary to follow them. Small transformers for operation on 2,200-volt circuits should receive a test of 10,000 volts for 1 min.

227. Tests on instrument transformers. Instrument transformers, if they are to be used for precise measurements, must have a calibration curve made for the conditions of load under which they will be operated. These calibration curves give the ratio and the phase displacement for different current-values. For methods of obtaining calibration curves on instrument transformers, see Sec. 3.

228. Instruments used for testing should be carefully chosen. The use of series (current) transformers and shunt (potential) transformers should be avoided unless they have been calibrated for the particular instruments to be used. In testing with high-voltage transformers at pressures above 50,000 volts, a sphere spark-gap should always be used, both for measuring the maximum of the applied voltage and also for the protection of both the testing transformer and the apparatus to be tested. The sphere gap can be relied on as an accurate method of measuring the maximum value of the applied voltage.*

INSTALLATION, CARE AND OPERATION

229. General. A transformer is usually very rugged and is capable of withstanding a great deal of abuse; nevertheless, it will be found to respond to good treatment by exhibiting longer life and higher operating efficiency.

*Farnsworth, S. W. and Fortescue, C. L. G. "Sphere Spark Gap;" *Trans.* A. I. E. E., Vol. XXXII, pt. 1, p. 733.
Chubb, L. W. and Fortescue, C. L. G. "Calibration of the Sphere-gap," *Trans.* A. I. E. E., Vol. XXXII, pt, 1, p. 739. Discussion by Peck, p. 812.

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230. Shipping and unpacking. Before leaving the factory, transformers are carefully packed. They are now generally shipped in their tanks with oil, and are ready for operation as soon as they arrive; but it is always a wise precaution, particularly with high-voltage transformers, to draw off from the bottom of the tank some of the oil and give it the usual disruptive test. If the dielectric strength is not high enough the oil should be dehydrated (Par. **239**). This may be done without removing the transformer from the tank, by drawing the oil from the bottom of the tank through the dehydrating outfit and returning it at the top; this should be continued until repeated tests show the oil to be in good condition. If the transformer has been shipped in a packing case, and is one of a high-voltage type, it should **be dried** out before installation, unless it is hermetically sealed in an air-tight metal casing. The safest and best method that can be used to dry out a transformer is to force dry air at a temperature of 90 deg. cent. through the windings. Grid resistances may be used for heating the air, and it may be forced through the windings by a blower.

231. Precautions in making connections. When installed ready for operation the transformers should be carefully inspected to see that they are all connected properly, both internally and externally; that all switching apparatus is in good working order; and if new banks are to run in multiple with previously installed banks, it should be noted that they are connected at the proper operating taps, and so as to have the same polarity as the older banks. If the new transformers are of the same manufacture as the old, the polarity will be the same as that of the old, if the banks are similarly connected. If they are of different manufacture from the old, the polarity when similarly connected may be such as to make parallel operation impossible. It is therefore a wise precaution to check up the relative polarity of the old and the new banks before connecting together. This may be done by connecting the new bank on the high-tension side and connecting one of the low-tension terminals to the common bus bar; then, with a voltmeter, and if necessary with the aid of a shunt (potential) transformer, measure the voltage between the other two terminals and the respective busses with which they are to connect (a bank of lamps may be used instead of a voltmeter, with 110- or 220-volt connections) and observe the following **rules:**

(a) **If the polarities are alike** the voltmeter will read zero, in each case.

(b) **If the polarities are reversed** the voltmeter will read, in each case, double the secondary voltage. The remedy is to reverse the connections of the low-tension leads of each transformer in the new bank. (In three-phase transformers it may be found more convenient to reverse the connections of the high-tension coils.)

(c) **In three-phase transformers** the following cases may be met, in addition to the above. Having two similarly located low-tension terminals, of the old and new banks, connected together, the high-tension terminals of each bank being similarly connected to the same source of e.m.f., measure the voltage between corresponding free low-tension terminals.

(c-1) **If one voltmeter reads the secondary voltage correctly and the other reads double this value,** the external polarity of the two transformers is the same, but the terminals are in different order. The remedy is to interchange the internal low-tension connections to the terminals of the new transformers, so that the lead connected to the terminal for which the voltmeter reads double voltage will take the place of the lead connected to the terminal tied to the corresponding terminal of the old transformer. Equivalent external transposition may be made instead.

(c-2) **If one voltmeter reads zero and the other reads 1.73 times the secondary voltage,** then we have a case of reversed external polarity and transposition of terminals, combined. The remedy in the case of a delta connection is to disconnect the ends of the two coils from the terminal showing high voltage and connect the other ends of these two coils to this terminal; the ends previously removed should then be connected to the two remaining terminals, so that a coil that was originally connected to any one of these two terminals will now be connected to the other one. An equivalent change of connections must be made in the case of a star connection.

232. Multiple connections. Transformers having like primary and secondary connections may be run in multiple with one another, but transformers having unlike primary and secondary connections cannot be made to run in multiple with the former except by the use of auxiliary devices,

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such as auto-transformers. It is of great importance, therefore, when buying transformers for multiple operation with previously installed banks, that the connections of the latter are given.

233. Where independent energy sources supply each bank of transformers, relative polarity is of no consequence, nor is it of any importance whether the primaries and the secondaries are both delta-connected, or one delta-connected and the other star-connected.

234. Causes of insulation failures. First, inadequate insulation strength at the point of failure. Second, imperfect mechanical supporting and bracing of coils, so that when subjected to the short-circuits that occur under operation, the coils are deflected or buckled, thereby tearing or weakening the insulation, which otherwise would be quite adequate. Third, poor design in the matter of cooling, such that while showing a normal temperature by thermometer or by rise of resistance, the windings have portions that are blanketed or far removed from the cooling medium; in other words, have "hot spots." Such a condition will, in the course of time, cause a weakening of the mechanical strength of the fibrous materials of which the insulation is composed, so that with the least jar the insulation is broken and an internal short-circuit results. Fourth, imperfect operation of apparatus on the line, such as circuit-breakers, electrolytic lightning arresters, etc. Fifth, improper operating conditions, such as overloading, or multiple operation without a proper division of load. Sixth, lack of care in regard to conditions of oil, dirt, moisture, etc. Seventh, direct stroke of lightning. Assuming that the transformer has been carefully designed in every feature, only the last four causes need receive consideration.

235. Line disturbances. The operation of circuit-breakers, charging of electrolytic arresters, breaking down of line insulators, and short-circuits on the line, all create disturbances which produce more or less stress on the transformer insulation; but transformers are insulated to withstand the stresses due to the above causes as they arise under normal working conditions. When, however, circuit-breakers fail to operate properly, these stresses may be unusually severe. It is therefore important to see that all protective devices are in perfect working order. With certain connections, such as the Scott connection and the "T"-connection, the charging of electrolytic lightning arresters may cause unusually severe stresses. The behavior of the transformers under such conditions should be carefully observed and if any unusual conditions are present they should be looked into.

236. Improper operating conditions are very often the source of transformer failures; particularly due to the fact that lack of care in other matters goes hand in hand with carelessness in operation. Conditions sometimes arise under which it is imperative that a transformer be overloaded for a considerable length of time. After such an overload, the transformer at the first opportunity should be examined to see that the ducts have not become clogged by any deposits from the oil. Transformers should not be operated for any great length of time on a system, one line of which has become grounded; the factor of safety in such operation is only one-half of that under normal operating conditions.

237. Grounded secondaries. Troubles may be caused when supplying energy for lighting from high-voltage polyphase circuits, due to the relative electrostatic capacity of the high-tension and low-tension circuits, to each other and to earth. This condition may cause high insulation stresses in the low-tension circuit, and may shock anyone touching the low-tension circuit sufficiently to cause death. The only remedy for this condition is to ground the secondary circuit, preferably at the neutral point. (See National Electrical Code, and also Sec. 12 and 13.)

238. Care of transformer oil. Lack of attention to such details as the periodic inspection of transformers, and testing of the oil, is responsible for most transformer failures. The oil in a high-voltage transformer should be tested once a month and if its strength is below par it should be dehydrated (Par. 239). It must be remembered that the oil furnishes one-half the insulation strength of the transformer.

239. The best method for dehydrating oil is by the use of the filter-press type of dehydrator. In this type the oil is pumped through several

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thicknesses of blotting paper. When using this apparatus it should be seen that the paper is carefully dried, and it is better to soak it, first of all, in clean oil that is perfectly dry. Fig. 50 shows this form of oil dehydrator. When the oil is in very bad condition, the paper should be changed from time to time, as often as found necessary. Oil in first-class condition should break down at not less than 40,000 volts, with a gap of 0.15 in. between ½-in. spheres.

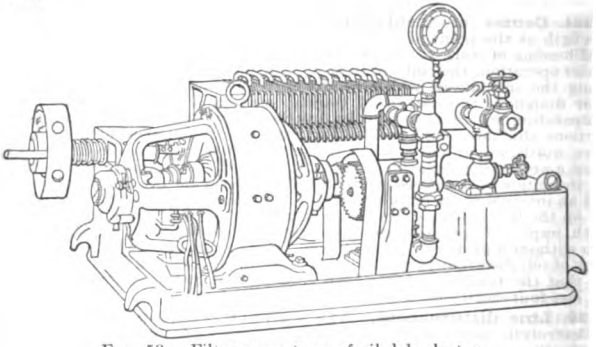


FIG. 50.—Filter press type of oil dehydrator.

240. Regulation of quantity of cooling medium. When water-cooled transformers are subjected to heavy overloads the water rate should be increased correspondingly. Any oil-immersed transformer will withstand a heavy load, for a short period very much better than an air-cooled transformer. Allowance should therefore be made in operation for the cooling characteristics of the transformers, and where artificial means are used for cooling, the cooling may be improved under abnormal load conditions by using more of the cooling medium.

241. The oil-piping layout of transformers when installed should be arranged so that the oil in any unit may be filtered without disturbing the others; there are several obvious methods of accomplishing this. Whatever scheme be used, care should be taken that all the air is removed from the oil in the transformer tanks; this may be done by creating a vacuum under the cover during the process of pumping.*

242. A transformer when burned out or defective should immediately be replaced by a spare unit if one is available. A careful examination should then be made of the windings; if nothing is disclosed, the transformer should be returned to its tank and measurements made of its open-circuit losses. If there are any short-circuited turns or layers, the open-circuit losses will be abnormally high. The location of the trouble can generally be traced by the blackening due to smoke, and by feeling the coils, after first removing the exciting voltage, for the point of highest temperature. If either of these methods fail, measurement may be taken of the resistance of primary and secondary windings; a short-circuit will be indicated by a lower resistance than normal. In many cases, however, a short-circuit which cripples the transformer may involve only a few turns in a large total number, so that the continuous-current resistance measurement may not be sensitive enough to detect it.

243. Formation of scale in cooling coils. A water-cooled transformer may progressively increase in temperature and appear to be defective, due to no apparent cause. In such a case the cause of the trouble can generally be traced to the water supply, which will be found to contain foreign matter in solution, such as lime and carbonates; these impurities, when the water becomes heated in passing through the tubes, are precipitated in the form of

* *Electrical World*, Feb., 1913, p. 360.

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scale, which, in addition to being a bad conductor of heat, chokes the flow of water.

244. Criterion for replacing inefficient transformers with units of higher efficiency. A transformer should be replaced by another of higher efficiency when the difference in cost of operating the two is greater than the interest on the additional capital that would be invested in the change. Opinions will differ in regard to the proper method of computing the cost of operating a transformer. The author's opinion is that the energy consumed in iron losses should constitute a fixed charge to the consumer depending upon his maximum demand. When it is found that by changing to a more modern line of transformers the fixed charge, after making proper allowances for interest and depreciation on both the old and the new, is less than the former fixed charge the change should be made.

REGULATORS

POTENTIAL REGULATORS

245. General principles. The principle of operation of all potential regulators consists in changing the mutual inductance between the primary and the secondary windings of a transformer or auto-transformer, either by mechanical means or by changing the ratio of the two windings.

246. The variable-ratio type of regulator is simply a transformer provided with means for changing the secondary e.m.f., either by cutting out portions of the winding, or by opposing or adding the e.m.f. of auxiliary windings of the transformer provided for this purpose. These auxiliary windings are provided with taps, so that their voltage may be increased or decreased, step by step. The secondary winding proper has only a few taps, the voltages of which are "bucked" or "boosted" by the auxiliary coils, according to the position of the regulator drum. In this way a large range of regulation may be provided with a comparatively simple equipment. Auto-transformers are sometimes used instead of the auxiliary windings. They have some advantage over the auxiliary winding scheme because finer steps are obtainable thereby.

247. The single-phase induction regulator depends upon mechanical means to produce this change in mutual inductance (Par. **245**). It consists usually of a stationary primary wound in a slotted field, and a secondary wound on a drum-shaped core which is rotatable with respect to the primary. The secondary e.m.f. is always practically in time phase with, or in time phase opposition to, the e.m.f. in the primary circuit.

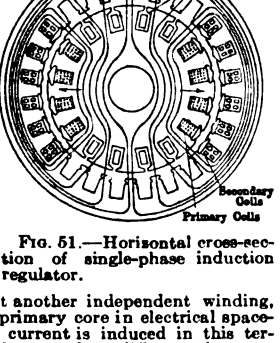


FIG. 51.—Horizontal cross-section of single-phase induction regulator.

248. The simplest conception of an induction regulator is a transformer with variable mutual inductance, and it may therefore be represented by the circuit shown in Fig. 4 (Par. **19**). When M becomes zero, the secondary inductance is L_2, which is very high: to overcome this defect another independent winding, short-circuited on itself, is wound on the primary core in electrical space-quadrature with the primary winding. A current is induced in this tertiary winding, depending upon the electrical space-phase difference between it and the secondary winding, which reduces the self-inductance of the latter.

249. Definitions of currents in a potential regulator. The secondary current is the line current, and the primary load current is that current which counterbalances the magnetizing or demagnetizing effect of the secondary current.

250. The variation of secondary e.m.f. with change in angular position, for a certain type of single-phase potential regulator is shown in Fig. 53. A vertical cross-section is shown in Fig. 52.

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251. The polyphase regulator in every essential detail, is a polyphase induction motor, the polyphase coil-wound rotor of which can be locked in any position desired. The primary windings are connected across the supply lines, precisely like the primary windings of a polyphase induction motor; however, the secondary phase-windings of the induction regulator, instead of being closed upon themselves, as is true of the secondary windings of an induction motor, are separately insulated and separately connected in series with the delivery circuits from the regulator. When polyphase e.m.fs. are impressed upon the primary windings, the e.m.f. generated in each secondary coil is of the same frequency as the primary e.m.f. and its value is entirely independent of the mechanical position of the movable member; the time-phase position of their e.m.fs., however, varies directly with the electrical space position of the movable member. (Compare with the single-phase induction regulator; see Par. **247**.) The resultant delivered e.m.f. is the vector sum of (or difference between) the primary and the secondary e.m.fs.; it is not constant in value but varies largely with the position of the movable member.

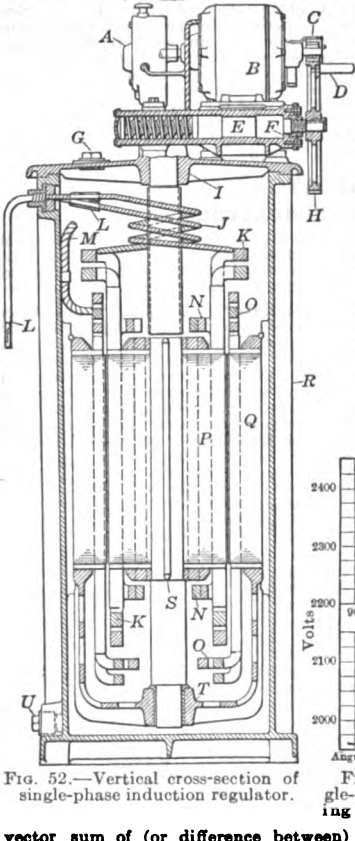


FIG. 52.—Vertical cross-section of single-phase induction regulator.

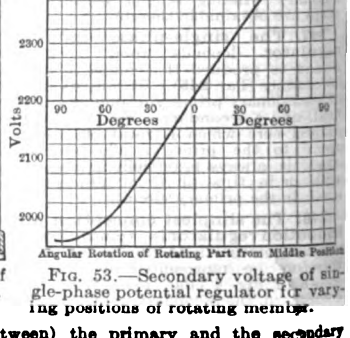


FIG. 53.—Secondary voltage of single-phase potential regulator for varying positions of rotating member.

252. Currents and m.m.fs. in polyphase regulators. The current in the delivery circuit (which is the same as that in the secondary coil) depends directly upon the delivered resultant e.m.f. and the impedance of the delivery circuit. In the polyphase induction regulator there is no special "tertiary" circuit, but each primary phase-winding acts in part as the tertiary circuit for the remaining primary phase-windings and the several secondary phase-windings. Thus the m.m.f. of the current in any secondary phase-winding, in any position whatsoever, is fully counterbalanced (except for magnetic leakage) by the m.m.f. of the current, or currents, of one

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or more primary phase-windings, and the reactance of the secondary is reduced to that due to the magnetic leakage between the stationary and the movable members.

253. Feeder voltage regulators, of either the step-by-step type or the induction type, may be operated by a motor, which in turn may be controlled by a voltage relay arranged to start the motor in positive or negative direction according as the voltage is low or high. A polyphase induction motor is usually employed, except when polyphase energy is not available; in this case a single-phase series motor may be used. The motor is stopped, when the relay opens, by means of a magnetically operated brake. The relay may be used in connection with a line-drop compensator (Par. 201), so that the voltage at the centre of distribution may be automatically kept constant at any desired value.

254. Pole-type feeder voltage regulators. Small feeder voltage regulators arranged for mounting on poles have been brought out by one firm of manufacturers. In many lighting systems, consumers may be supplied from one common feeder in such a way that there is no definite centre of distribution; thus consumers on short branch feeders may receive perfectly satisfactory service, whereas others served from long branches may receive poor service due to the larger drop in such branches. It is claimed that a saving may be effected by installing one of these pole-type, automatic, feeder voltage regulators instead of increasing the cross-section of the branch feeders. The regulator proper consists of a shuttle-shaped rotor on which the primary is wound in one coil; the rotor also carries the tertiary short-circuited winding. The secondary is a single, form-wound, undistributed winding, fitting in two slots in the stationary core.

The regulator is operated by a single-phase induction motor provided with a starting clutch, and is controlled by a voltage relay which may be adjusted for any voltage from 10 per cent. above to 10 per cent. below normal. The relay may also be used in connection with a line-drop compensator, which has to be installed outside of the regulator. The regulator and mechanism are suspended in a cast-iron tank, and the lower part, containing the regulator core and coils, is filled with oil.

255. Vector diagram of e.m.fs. in polyphase regulator. Referring to Fig. 54, let OA represent the e.m.f. of a certain primary phase both in value and time-phase position. Let OE (or OD) represent the e.m.f. of the corresponding secondary phase-winding in the maximum positive (or maximum negative) boost position. Let OE (or OD) simultaneously represent the mechanical position (in electrical space degrees) of the moving member when the secondary e.m.f. is in time-phase with (or time-phase opposition to) the primary e.m.f. In any mechanical position of the moving member, such as OD, the secondary e.m.f. has a value equal to OE (or OD) and its timephase position is correctly represented by the line OL provided that the "revolving field" which is the resultant of the fluxes set up by the separate primary phases is constant in magnitude. In Fig. 54 the primary e.m.f. is OA and the secondary e.m.f. is OB, the resultant e.m.f. is AB.

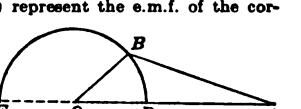


FIG. 54.—Vector diagram of polyphase inductor regulator.

CURRENT REGULATORS

256. General principles. This apparatus generally consists of an adjustable reactance, which may comprise a winding on an open magnetic circuit. The coil is counterbalanced, so that with a change in the load reactance the coil will so adjust itself with respect to the core that there will be no change in the value of the current. If a large reactance be placed in series with a lesser non-inductive resistance, and a constant e.m.f. be impressed, the current will vary but slightly with this resistance "all in" or "all out" of circuit. The actual ratio of the currents with resistance "all in" and "all out" will be equal to the value of $\sqrt{1-(\text{power-factor})^2}$, the power-factor being the value with resistance all in. It is evident that if the operating power-factor be made low enough, a series system of incandescent lamps may be operated at constant current, from a constant-potential source, with very little variation in the series reactance.

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257. Limitations. The constant-current regulator has a limited application combined with a vapor convertor for supplying light for motion picture machines, but for general lighting it cannot advantageously take the place of the constant-current transformer, since it requires an additional transformer for insulation purposes (see National Electrical Code).

258. Types and characteristics. The usual type manufactured is air-cooled and of the form described in Par. **256.** An automatic constant current regulator may also be made by connecting in opposition two coils which surround a closed magnetic circuit, using their leakage reactance for the regulating reactance. The two coils are pivoted so as to approach each other at the middle of the core. In action they will repel each other with a force nearly proportional to the current, for any position; with proper counter weight, therefore, the current will automatically be kept constant.

259. A motor-controlled potential regulator may be used as a constant-current regulator by controlling it from a constant-current relay; it is usually, however, too sluggish in operation to give perfect satisfaction.

REACTORS

260. General types. Reactors, choke coils, or reactances for power purposes may be divided into two classes, viz., those in which iron is used and those in which no magnetic material whatever is used. The first type consists of a coil encircling a circuit of iron which is usually broken by an air-gap or a series of air-gaps. The second type is simply a carefully constructed, circular coil of rectangular cross-section, of suitable proportions for cooling, and well supported mechanically.

261. Iron core reactances. The fundamental equations and general design are the same as for constant-potential transformers. The air-gap should be subdivided so as to avoid concentrated leakage, which causes eddy currents in the conductors (which are difficult to eliminate) and also makes it difficult to calculate the reactance accurately. The relative amount of copper and iron will be determined largely by the condition for minimum cost, but where the conductors are very large, it is advisable to increase the area of the core and reduce the number of turns in order to keep down the eddy-current losses in the conductors. In winding with multiple conductors every care should be taken to see that the reactance of each conductor and its resistance is the same; this may be accomplished by properly distributing the "start" and "finish" leads of the conductors.

If the length of the air-gap is l, the required inductance L, the current I, the number of turns n, the effective area of the air gaps must be obtained and it will depend on their number and distribution. The value of $\mathfrak{B}$ may then be calculated from this area by Eq. 4, Par. **5.**
Thus the value of l will be

$$l = \frac{4.51 n I}{\mathfrak{B}} \quad \text{(in.)} \qquad (77$$

where $\mathfrak{B}$ is the induction in lines per sq. in.

262. The current densities and the flux densities will be about the same as for transformers. The methods of insulating the coils are very similar and need no special treatment here, as they are covered under the heading of "Insulation," Par. **41** to Par. **47.**

263. Cooling may be effected by any of the various methods applied to transformers. The problem is the same in every particular and is treated under that heading, Par. **61** to Par. **70.**

264. Applications. Iron reactors for power purposes are most used in connection with compound-wound rotary converters to obtain compounding or overcompounding of the voltage at the continuous-current terminals. Iron reactors are also used to shunt the series coils of compound-wound continuous-current machines, in which case they are known as **inductive shunts.** They may be used for innumerable purposes, such as compensating for the leading current in cable testing; for compensating long telephone circuits (**Pupin coils**); shunting series incandescent lamps (**economy coils**) to prevent an open circuit as the result of a lamp failure, etc.

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265. Air reactors for precise measurements are made of a single layer of fine enameled wire, carefully wound on a marble cylinder that has been made as nearly perfect as possible; such reactors are used as absolute standards. Power-limiting reactors are described in Par. **266** and **267**. The **reactance circuit-breaker** makes use of an air reactance to limit the current at the initial break so that a circuit may be opened in two stages; the first stage being the introduction of the reactance, and the second stage being the complete opening of the circuit. Air reactors have also been put into service for supplying lagging current to compensate for the leading current due to the distributed capacity of transmission lines; and are inserted in series with transmission lines (**choke coils**), for protection against lighting disturbance. Their office in the last instance is to choke back any line surge that may arise and prevent it from injuring the station apparatus.

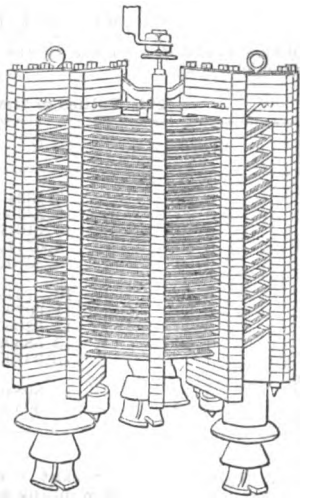


FIG. 55.—Power-limiting reactor.

266. Power-limiting reactors are now usually made with no magnetic material, although the first reactors made for this purpose and installed in the Cos Cob station of the New York, New Haven & Hartford Railroad Co. were of the iron-core type with distributed windings.

267. Methods of winding power-limiting reactors. The methods of winding adopted by the various manufacturers do not differ materially. Thus one firm winds with long cylindrical layers, using wooden cleats as separators; another firm uses flat discoidal-shaped layers or sections, each conductor of which fits into a groove in porcelain cleats; the cleats when clamped together insulate and separate the individual layers. A third firm uses methods similar to the second, but for cleats employs moulded heat-resisting material as a substitute for porcelain. See Fig. 55.

268. Cooling of power-limiting reactors is effected by natural circulation or air blast. The arrangements of winding are particularly well adapted for cooling by the last method.

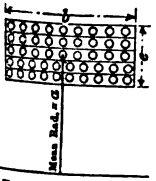


FIG. 56.—Cross-section of reactance coil.

269. Mechanical stresses in the windings, while severe, are not of such a nature as to produce any trouble. Thus the radial stresses tend to elongate the conductors, while at the same time they produce a compressive action on the coil section. The axial stresses are compressive and tend to crush the conductors into less space. These forces are difficult to calculate with any degree of accuracy, but experience has shown that with the methods of winding which have been described, and with reasonable care in installing, reactors will be amply strong enough to withstand any stress that may arise in service.

270. Formulas for self-inductance; Rosa's formula. This is accurate for any shape of coil. For practical work the correction for the form of the conductor is negligible and may be omitted; the formula then becomes

$$L = L_s - \Delta_1 L \qquad (78)$$

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To obtain the value of L_s the formula below may be used (Eq. 79):

$$L_s = an^2Q \times \frac{2.54}{10^9} \quad \text{(henrys)} \qquad (79$$

Where Q is a function of $2a/b$, the values of which for different values of thi ratio are given in the table below, in Par. **271**. The correction term $\Delta_1 L$ i given by the formula

$$\Delta_1 L = 4\pi a\left(\frac{b}{c}\right)(A_s + B_s) \times \frac{2.54}{10^9} \quad \text{(henrys)} \qquad (80$$

Where A_s and B_s are given in the tables below (Par. **272** and Par. **273**) a functions of c/a.

271. Values of the Constant Q in Eq. 79

$2a/b$	Q	$2a/b$	Q
0.20	3.63240	1.80	19.57938
0.30	5.23368	2.00	20.74631
0.40	6.71017	2.20	21.82049
0.50	8.07470	2.40	22.81496
0.60	9.33892	2.60	23.74013
0.70	10.51349	2.80	24.60482
0.80	11.60790	3.00	25.41613
0.90	12.63059	3.20	26.18009
1.00	13.58892	3.40	26.90177
1.20	15.33799	3.60	27.58548
1.40	16.89840	3.80	28.23494
1.60	18.30354	4.00	28.85335

272. Value of the Constant A, as a Function of c/a, c being the Dept of the Winding and a the Mean Radius

c/a	A_s	c/a	A_s
0.00	0.6949	0.20	0.6922
0.10	0.6942	0.25	0.6909
0.15	0.6933		

273. Values of the Correction Term B, Depending on the Ratio b

b/c	B_s	b/c	B_s	b/c	B_s
1	0.0000	11	0.2844	21	0.3116
2	0.1202	12	0.2888	22	0.3131
3	0.1753	13	0.2927	23	0.3145
4	0.2076	14	0.2961	24	0.3157
5	0.2292	15	0.2991	25	0.3169
6	0.2446	16	0.3017	26	0.3180
7	0.2563	17	0.3041	27	0.3190
8	0.2656	18	0.3062	28	0.3200
9	0.2730	19	0.3082	29	0.3209
10	0.2792	20	0.3099	30	0.3218

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RECTIFIERS

VAPOR TYPE RECTIFIERS

274. The mercury-vapor rectifier is exceedingly simple in structure. The single-phase type consists of a chamber from which the air and all foreign gases have been exhausted, and in which there is a mercury pool connected to a terminal which passes through the chamber; projecting into the upper part of chamber are two terminals of iron or graphite which are commonly called the **anodes** (but which in actual service are alternately anode and cathode), the mercury pool being termed the **cathode.** The general arrangement is shown in Fig. 57. In addition to the above, there may be **a supplementary anode** which may be a separate rod or, in **glass-bulb** rectifiers, a portion of the mercury pool separated from the remainder by a slight space. This supplementary anode is used for starting or exciting the rectifier; when used for starting only, a tilting mechanism is provided which enables the two edges of the mercury pool to be brought together, closing an auxiliary circuit, and thus causing a spark or arc to form where the edges recede. Once the rectifier starts, it will continue to operate if the proper amount of inductance is included in the circuit. Where the supplementary anode is used for continuous excitation, it is connected to a source of direct current. Where the mercury pool is divided into three small pools, the two outer pools may be used as anodes with the centre pool as cathode, and a continuous arc may be supplied for sustaining purposes by means of a small auxiliary transforming device or auto-transformer.

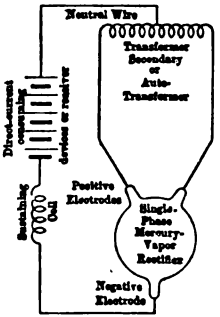


FIG. 57.—Single-phase Mercury-vapor rectifier.

275. Characteristics. From the viewpoint of the electrical engineer the mercury-vapor rectifier may be considered as an electrical valve, which permits current to flow only from a positive terminal to the pool of mercury. Thus, as long as the terminal has a certain definite potential above that of the mercury pool, current will pass, but the moment that this potential becomes lower than this critical value, the current commences to decrease.

276. The theory of operation. An ionising agent is required to start the electron stream issuing from the cathode. The liberated electrons proceed at high velocity toward the anode ionising molecules of gas on their course thereby producing positively charged bodies and increasing the stream of electrons moving toward the anode. The positive charges are drawn toward the cathode where they become neutralized again or negatively charged; in so doing they further increase the ionization at the cathode, and produce in its neighborhood a high intensity or potential gradient which assists in accelerating the electrons emitted at the surface of the cathode. The neutral or negatively charged molecule is forced back toward the anode, but becomes ionized again by the stream of electrons issuing from the cathode. The negatively charged molecules apparently rarely move far enough away from the cathode, before becoming ionised by collision, and positively charged, so as to come under the influence of the electric field of the inactive electrode. There is, therefore, no leakage or an extremely small one between the active and inactive anode.

277. The thermionic or hot cathode rectifier consists of a tungsten anode and a hot filament cathode, which is heated by a separate circuit; both are contained in a highly evacuated bulb. **The theory of operation** is as follows: The hot cathode emits electrons at a rate corresponding to the flow of current required, until the limit set by the Richardson curve is reached; from this point on the rate of emission of electrons remains constant for a given temperature of the cathode. Any further increase merely reduces the spaced charge in the bulb, increasing the difference of potential between anode and cathode, and thereby increasing the velocity of the electrons. The kinetic energy so imparted is dissipated in the form of

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heat at the anode due to its bombardment and in radiation in the form of X-rays. **Recent improvements** make use of an inert gas argon which affords the means for producing more electrons by collision, so that a double action takes place similar to that in the vapor convertor, and the limitation due to the Richardson effect is no longer present.

278. Auxiliary apparatus. The **vapor convertor** requires a transformer or auto-transformer with a tap at the middle point so that both half waves of the alternating current supplied are utilized; this is necessary in order to give the necessary sustaining effect, which must be further enhanced by a choke coil in series with the direct-current circuit or its equivalent, incorporated in the design of the transformer; otherwise the rectifier would become deionized and go out. The hot cathode (argon filled) convertor does not require sustaining and it is not necessary to utilize every half wave. A single anode may therefore be used and the whole arrangement is simpler and cheaper than that for the vapor convertor.

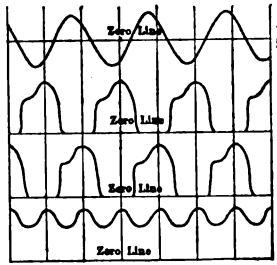


FIG. 58.—Typical wave form of single-phase rectifiers.

279. Typical waveforms obtained in a low-voltage self-sustained vapor convertor are shown in Fig. 58.

280. The three-phase rectifier, shown in Fig. 59, is unlike the single-phase rectifier in the respect that it requires no inductance to sustain the direct-current wave. This will be better understood by referring to Fig. 60, where *a*, *b*, *c*, are the consecutive positive voltage waves of a three-phase system. The secondary current will flow first from the anode connected to phase *a*, to the cathode, and thence through the direct-current circuit back to the neutral point of the three-phase system. This will continue until the point *h* in the wave *a* is reached; the current will then be transferred to the anode connected to the phase *b*; the current will continue to flow from this wave until the point *k* is reached, when it will again be transferred, to the wave *c*; it will continue to flow from *c* until the point *e* is reached, when it will once more be transferred to the wave *a* completing the cycle. The dotted line represents the cathode potential with reference to that of

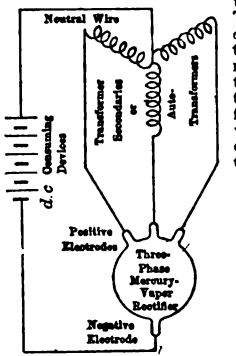


FIG. 59.—Three-phase mercury-vapor rectifier.

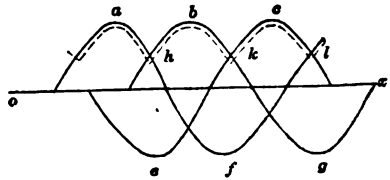


FIG. 60.

the neutral point of the three-phase system; the latter is the positive terminal of the direct-current system supplied by the rectifier, its potential being represented in Fig. 60 by the line (*ox*).

281. With the advent of high-efficiency (nitrogen-filled) incandescent lighting and the use of carbon flame, alternating-current lamps

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...r brilliant street lighting, the demand for vapor converter equipments for ...pet-current constant-current lighting (metallic flame, magnetite arc ...p) has ceased. Vapor convertors are still being manufactured and ...plied for existing installations.

283. Small low-voltage vapor convertors were manufactured for ...me **charging outfits** for charging batteries for electric vehicles, but ...e demand for such equipments has become very small, owners of such ...chines preferring to keep them at garages where the charging is done with ...ge 30 to 50 amp. equipments.

283. Small charging equipments for starting batteries. The 10-...pere vapor convertor equipment is replaced by the thermionic (argon filled) ...nvertors rated as follows:

... 2 ampere	15 volts max.
... 6 ampere	15–30 and 75 volts max.

284. Vapor convertor equipments for moving pictures (30 to 50 ...peres) are being displaced by incandescent nitrogen-filled lamps run at ...gh efficiency with a guaranteed life of 100 hours.

285. Vapor convertor equipments for charging telephone batteries ...th ratings of 10, 30 and 50 amperes, are still being supplied, but it is ...robable that the smaller thermionic outfits will take their place, on account ...f the fact that the latter do not require sustaining and therefore may be ...erated the whole 24 hours without attendance.

286. Vapor convertors for power service. Development of the iron ...lad type of vapor convertor was discontinued during the war but there are prospects that it will be taken up again. Such an equipment was used successfully in America for operating a railway car at 5,000 volts direct-current in an experimental installation at Grass Lake, Michigan.

ELECTROLYTIC RECTIFIERS*

287. Theory of operation. It has been found that when a plate of aluminum and a plate of lead or carbon are immersed in certain solutions, an electric current can be made to pass in one direction, but not in a reverse direction. In other words, this combination will act as an **electric valve** and is the basis upon which the electrolytic rectifier and electrolytic lightning arresters are designed. The more complex the acid radical employed in the solution of the electrolyte, the more complete will be the valve action with a given voltage, or, in other words, the higher will be the voltage which may be satisfactorily rectified. In view of this fact, recent developments have been made in the use of ammonium phosphate or sodium borate dissolved in water, as the basis of the electrolyte.

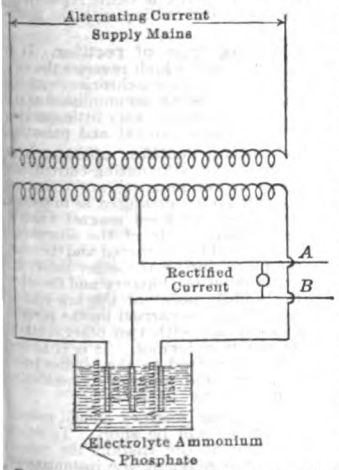


Fig. 61.—Diagram of electrolytic rectifier.

The electrolytic rectifier, therefore, consists essentially of two aluminum plates and a lead plate immersed in a solution of ammonium phosphate and connected to some transforming device, as shown in Fig. 61. Such an arrangement will allow the current to pass from the lead plate, but never from the aluminum plates, with the result that the current flowing between the terminals marked A and B will be unidirectional, but pulsating.

*See Sec. 19.

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288. General characteristics. Such a rectifier is comparatively cheap, simple to construct, requires no sustaining circuits, and to this extent is satisfactory for handling very small loads where the service is intermittent.

289. The efficiency of the rectifier is relatively low, seldom exceeding 60 per cent. and frequently averaging much less. The efficiency increases with decrease in the amount of current to be rectified.

290. Heating. Since the efficiency is low, the heat loss in the rectifier is comparatively large, which results in rapid deterioration of the plates. The degree of rectification, as the temperature rises, is much less complete. In other words, the leakage of current becomes excessive as the current increases, unless cooling means are provided.

291. Treatment of plates. A further objection to the electrolytic rectifier is the necessity for occasionally "treating" the plates to form the necessary insulating and rectifying films.

292. General applications. As a result of the low efficiency, the rapid deterioration, and the rapid heating of the electrolytic rectifier, it is seldom used for ordinary loads. Its present field appears to be limited to X-ray equipments and experimental purposes where a cheap rectifying device is required for light intermittent service.

293. Artificially cooled electrodes. Recent improvements have been made in electrolytic rectifiers which permit operation at higher current densities. One of these consists in cooling the aluminum cathode by a stream of water. The effect is such that a current ten times as large can be permitted with the cooled cell as with the same cell uncooled. An excellent rectifying effect with a cooled cell may be obtained with frequencies as high as 4,000 to 10,000 cycles per second.*

MECHANICAL RECTIFIERS

294. The vibrating type of alternating-current rectifier is a simple efficient and inexpensive piece of apparatus adapted particularly to the charging of three-cell vehicle batteries. However this type is being replaced by the thermionic converter, which overcomes the difficulties with the mechanical type due to sparking contacts.

295. General characteristics of vibrating type of rectifier. It is essentially an electrically operated vibrating switch which reverses the connection of the alternating-current line to the battery in synchronism with the alternations of the current, this reversing action being accomplished at the moment when the current flow is zero. There is therefore very little sparking at the contacts and the current delivered is unidirectional and pulsating.

296. The principle on which the vibrating rectifier operates is as follows: a small transformer serves to reduce the alternating-current line voltage to a suitable value; two alternating-current magnets are connected across one-half of the low-voltage winding and are so arranged as to present at any instant poles of like polarity before those of a steel magnet which is excited from the battery. Hence during one-half cycle of the alternating current, one of the poles of the pivoted magnet will be attracted and the other repelled, and the opposite action will take place during the other half-cycle. The pivoted magnet is connected to one terminal of the battery and the other terminal of the latter is connected to the middle point of the low-tension winding of the transformer. Two platinum contacts carried on the pivoted magnet are thereby brought alternately in contact with two other contacts connected to the low-voltage terminals of the transformer. It is of no importance which terminals of the battery are connected to the binding posts of the apparatus, since the winding of the pivoted magnet automatically determines the proper polarity of the binding posts.

297. Sparking. A properly designed vibrating rectifier should operate without sparking, otherwise the life of contacts will be short. To secure sparkless operation, contact should be broken at the instant the current falls to zero and should be made again at the moment the instantaneous value of the alternating voltage wave is equal to the e.m.f. of the storage battery. If contact is broken before the current reaches zero and made again some time after the alternating e.m.f. has reached the proper value, the max

* See *Elek. Zeit.*, Aug. 21, 1913. *Phys. Zeit.*, June 15, 1913.

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mum input to the battery will not be obtained; on the other hand, if the current reverses before contact is broken, part of the battery charge will be dissipated in the circuit.

When the wave-form of the alternating-current supply differs from a sine-wave it may be necessary to change the adjustment slightly to prevent sparking. This may be accomplished by means of a variable resistance in series with the alternating-current magnets, which permits the time-phase lag of the magnetizing current behind the secondary e.m.f. to be adjusted until sparkless operation is obtained.

298. Ratings and efficiency. The efficiency is usually about 55 per cent. Commercial types are made for operation on 60, 50, 40, or 25 cycles, at 110 volts. They are designed to charge 3 cells of storage battery and deliver a current of from 8 to 8.5 amp.

299. A commutator type rectifier is being manufactured by one company for charging small batteries.

300. Other forms of mechanical rectifiers. Mechanical synchronous contactors are used for rectifying alternating-current waves so that direct-current galvanometers may be employed for precise and delicate measurements on alternating-current circuits. Since it is essential in such cases to reverse the contacts as quickly as possible, so that as much as possible of the alternating waves shall be rectified, these devices are costly and require a great deal of care in their design. Some high-voltage contact rectifiers have also been devised for laboratory work.

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SECTION 7

ALTERNATING-CURRENT GENERATORS AND MOTORS

BY

COMFORT A. ADAMS

Professor of Electrical Engineering, Harvard University; Fellow American Institute of Electrical Engineers

AND

HENRY M. HOBART

Consulting Engineer, General Electric Co., Fellow American Institute of Electrical Engineers

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SECTION 7

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SYNCHRONOUS MACHINES

GENERAL

1. Definition. A synchronous generator (or motor) usually consists a system of alternately north and south magnetic poles, comprising th field, which moves with respect to a system of suitably connected co ductors in which the alternating e.m.f. is induced. These conductors t gether with their mounting are called the armature. See Fig. 1. Th magnetic poles of the field are usually excited with direct-current supplie by a separate generator called an **exciter**. See Par. 9.



FIG. 1.—A portion of the armature and field of a synchronous machine.

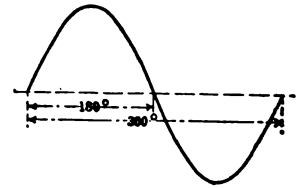


FIG. 2.—A graph of a cycle of e.m.f.

2. The "cycle." In the ordinary heteropolar alternator, the e.m. induced in each armature conductor reverses with the passage of each pol i.e., for a peripheral movement equal to one pole pitch (the peripheral distan between the centres of adjacent poles). The set of values comprised withi a double reversal, or corresponding to a movement equal to twice the po pitch, repeats itself indefinitely, and is called a cycle of values, or simply cycle. See Fig. 2. The graph of these values plotted against time in re tangular coordinates, is referred to as the **e.m.f. wave** of the machine i question.

3. Frequency. The time required for the execution of a cycle is calle the **period** of the alternating e.m.f., and the number of cycles per secon is called the frequency. Frequency, f, is expressed by the relation: $f = p$ rev. per second, where $2p$ is the number of poles. Modern commerci frequencies in the United States are 60 and 25 cycles per sec.

4. Electrical and magnetic degrees. It is customary to refer to a cyc as 360 electrical degrees (see Fig. 2), or one electrical revolution, and to th circumferential distance from the centre of one pole to that of the ne

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of the same polarity, as 360 magnetic degrees. Thus two active armature conductors displaced from each other by β magnetic degrees will experience e.m.fs. differing in phase by β electrical degrees. Two active conductors 360 magnetic degrees apart would naturally be connected in series to form a loop or coil, since their two e.m.fs. will then be always in the same direction around the circuit of the loop (see coils I and II, Fig. 3).

5. The two-phase (quarter-phase) alternator. Referring to Fig. 3, coils I and II are displaced from each other by 90 magnetic degrees. The



FIG. 3.—Part of the armature and field of a quarter-phase alternator.

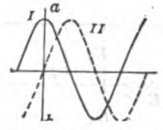


FIG. 4.—Graph of the electromotive forces in a quarter-phase alternator, plotted against time.

e.m.fs. induced in these two coils therefore differ in phase by 90 deg. If all coils in the same phase as I, are connected in series, and all those in the same phase as II in another series, the two circuits being separate and distinct electrically, the machine is called a two-phase machine. The circuits themselves are referred to as the two phases or phase windings of the machine. Sometimes this type of machine is called a quarter-phase machine, since its two e.m.fs. differ in phase by 90 deg. or one-quarter cycle. The electromotive force in coil I is zero when that in coil II is a maximum, and *vice versa*. If the value of the electromotive force from instant to instant is a sine function of the relative angular position of the armature coils and revolving field, the curves of the electromotive forces in coils I and II, may be plotted as indicated in Fig. 4, in which the ordinates represent the instantaneous values of the electromotive force, and the abscissas represent time. The four terminals of the two windings of a two-phase alternator are usually brought out to the terminal board. The load may be fed by three wires, one the common return for the other two, or four wires may be employed as two independent circuits.



FIG. 5.—Part of the armature and field of a three-phase alternator.

6. The three-phase alternator. If three sets of overlapping coils displaced by 60 magnetic degrees (Fig. 5) be connected to three separate cir-

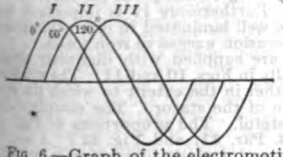


FIG. 6.—Graph of the electromotive forces in the three armature circuits of a three-phase alternator.

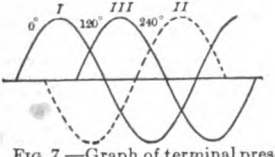
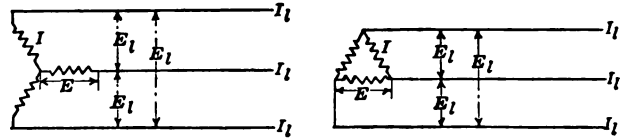


FIG. 7.—Graph of terminal pressures in the three phases of a three-phase alternator.

cuits, their e.m.fs. will differ in phase by 60 deg. (see Fig. 6). By reversing the terminal connections of phase II, we reverse the phase of its e.m.f. with respect to the load and obtain the three voltages shown in Fig. 7. These voltages differ in phase by 120 deg. The difference between the three e.m.fs. of Fig. 6 and those of Fig. 7 is obviously external to the machine in which they are generated, which is called a three-phase alternator. In many three-phase

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alternators the phases are internally connected, with only three termin brought out. There are two principal methods of making these connectio Y and Δ (see Figs. 8 and 9). Let E and I represent respectively volts a amperes per armature phase; and E_l and I_l the line volts and amper Then, in the Y armature, $E_l = E\sqrt{3}$, and $I_l = I$; and in the Δ armatu $E_l = E$, and $I_l = \sqrt{3}\, I$. Therefore the power in each case will be $3EI$ co $= \sqrt{3}\, E_l I_l \cos\theta$, where θ is the common phase difference between the vo tage and current of each phase, balanced load assumed.



FIGS. 8 AND 9.—Internal and external e.m.fs. and currents in three-phase a ternators with Y and Δ connections.

7. Note on phase classification. There is a slight inconsistency i the usual classification of alternators and systems. In the ordinary thre phase alternator (Fig. 5) there are, in each 360 magnetic degrees of circu ference, six coil groups or belts of conductors. In these groups a being generated six different e.m.fs. differing in phase progressivel by 60 deg. or one-sixth of a cycle. If the six terminals of t three phases be connected to three equal loads, the six currents in the s leads, when counted positive in the same direction along the line, will diff in phase progressively by 60 deg. If, however, the three phases be connecte in Y or Δ, with three leads connected to the load, the three currents, counte positive in the same direction along the line, will differ in phase by 120 de or one-third of a cycle. To be consistent these two systems should be referre to as "six-phase" and "three-phase" respectively, although the alternat is the same. Moreover when a closed-coil armature is used for alternatin e.m.f. generation, as in the case of a synchronous converter, it is calle "three phase" when it has three 120-deg. taps and three phase-belts 120-deg. span, and six phase when it has six 60-deg. taps and six phase-bel each of 60-deg. span. Thus, to be consistent, the ordinary three-pha alternator should be called a six-phase alternator, although mostly us to supply three-phase circuits.

8. Single-phase generators* are occasionally required for railways an also for certain electrochemical and electrothermal processes. Mo single-phase generators are simply Y-connected three-phase generato with one of the three legs left idle. When a generator is operate single-phase, it is important that the pole shoes should be fitted wit a heavy amortisseur or squirrel cage winding to damp out the effects of th pulsating armature reaction (Par. 44). Furthermore it is important tha all parts of the magnetic circuit shall be well laminated in order that puls tions in the resultant m.m.f. may not occasion excessive iron losses.

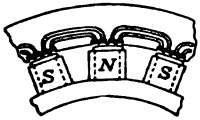
Occasionally single-phase generators are supplied with distinctly singl phase windings as shown diagrammatically in Figs. 10 and 11. The windin in these two figures differ from one another in the extent to which the co ductors are distributed over the surface of the stator. The complete di tribution employed in Fig. 11 is wasteful. The proportions of Fig. 1 are more nearly correct. (See Par. 28, Par. 31, and Fig. 32.) A singl phase generator for a given kv-a. output and a given power factor, voltag and speed, is inherently more heavy and expensive than the equivalent poly phase generator by fully 65 per cent. Even then, if the speed is very high, a

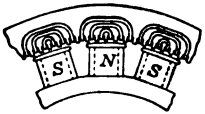
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In the case of a steam turbine-driven generator, the temperature rise will be greater and its efficiency will be lower than in the case of the polyphase machine. Very few manufacturers of dynamo-electric machinery have realized the difficulties attending the design and construction of single-phase generators, and many faultily designed machines have been built. Singular as it may seem, there is even now a general failure to pay heed to these unsuccessful results. Even for cases where polyphase machines are required to carry differing loads and power-factors on the various phases, the heating may be decidedly excessive unless such machines are designed with due regard to the pulsating m.m.f. which will be present under these conditions of load.





FIGS. 10 AND 11.—Single-phase alternators with distinctly single-phase windings.

9. **Excitation:** Separate excitation is almost always employed in modern synchronous generators. The exciter is usually either mounted on an extension of the main generator shaft or driven by a motor from the generator bus. This is, however, objectionable in that a given percentage variation in the speed of the generator will occasion a greater percentage variation in its voltage. Thus if, for instance, the speed varies 1 per cent., the speed of the exciter will vary 1 per cent. and the voltage of the exciter by a little more than 1 per cent.; this causes a little more than 2 per cent. variation in the voltage of the main generator. It is, therefore, desirable that exciters be driven by independent prime movers whenever it is possible. Various methods have been devised for rendering alternators self-exciting but, except for comparatively small machines, these are never used.

10. **Relative motion: revolving armature and revolving field.** The revolving-armature type of alternator is now rarely employed even in very small sizes. Revolving-field alternators fall into two classes: (*a*) those with cylindrical rotors provided with windings embedded in slots in the surface; (*b*) those with salient-pole rotors. The former are now almost universally used for extra high-speed generators driven from steam turbines, owing to stronger mechanical construction, better balance, less noise and lower air friction (which last may represent a loss as great as the aggregate of all the others). For water-wheel generators and for generators driven by reciprocating engines the salient-pole construction is usually the most appropriate, although, for other than very low speeds, a good argument can usually be presented for the cylindrical type of rotor.

11. **Vertical and horizontal types.** Until 1911 a considerable proportion of the steam turbine-driven alternators were of the vertical type. The subsequent large increase of speeds of steam turbo-alternators (in many cases double) involving greater lengths, smaller diameters, and greater vibrational difficulties, has made more desirable the horizontal type with its inherently better provision for strength of frame and accessibility of parts. The vertical type is generally used for low-speed water-wheel generators. As a notable instance of the vertical type may be mentioned the 30 Keokuk generators, each 9,000 kv-a., 25 cycles and 55 r.p.m. with 52 poles. The external diameter of the rotor is 25 ft. and it weighs 116 tons. The entire machine weighs some 275 tons.

12. **Engine type.** (Direct-connected to reciprocating engines.) In this type sufficient momentum must be provided in the rotating element to ensure the required degree of uniformity in the angular velocity. Three arrangements to accomplish this end are: (a) a separate fly-wheel; (b) the fly-wheel as an integral part of an internal rotor, Fig. 12; (c) the fly-wheel as an integral part of an overhung rotor, Fig. 13.

In America the fly-wheel effect is expressed in terms of the WR^2 where the weight of the rotor in pounds is denoted by W, and the radius to the centre of gyration, in feet, is denoted by R. In countries employing the metric

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system, the fly-wheel effect is expressed in terms of the GD^2, where D is th diameter at the centre of gyration in meters, and G is the weight of the roto in kilograms. The greater the weight of the required fly wheel, the more liberal must be the design of the bearings

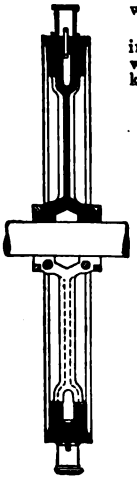


FIG. 12.—Fly-wheel rotor for alternator.

13. Water-wheel type alternators have speeds rang ing widely in accordance with the head of water unde which the prime movers operate. The Keokuk 9,000 kv-a. generator (Par. 11) has a rotative speed of 58 rev

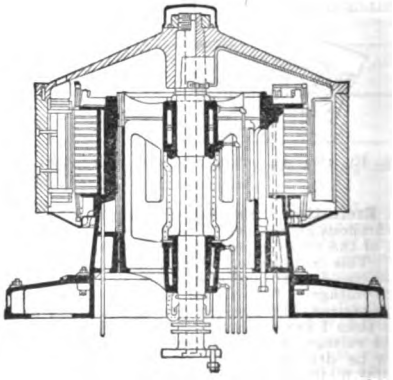


FIG. 13.—Umbrella type of revolving-field alternator.

per min., and the 5,000-kv-a. (Niagara) generator (Fig. 13) 250 rev. per mi

Even for the same head, water-wheels are built for any speed within quit a wide range. On the whole, the water-wheel will be lower in price and mo efficient when constructed for a moderately low speed. On the other han the weight and cost of the generator will decrease with increasing rate speed, up to fairly high speeds. At all but very low heads, therefore, th tendency is toward fairly high speeds. For 10,000 to 20,000 kv-a. wate wheel sets, speeds of some 300 to 600 rev. per min. are now often employe In event of accident to governors or head-gates, the runaway speed will ap proach double the normal speed; see paper in Vol. XXXI of Trans. A. I. E. E by D. W. Mead entitled "The Runaway Speed of Water-wheels and it Effect on Connected Rotary Machinery," and a paper by F. Nagler, entitle "A New Type of Hydraulic Turbine Runner," at p. 921 of "*Mechanica Engineering*" for December, 1919. Water-wheel driven generators hav been built up to capacities of 22,000 kv-a. in the horisontal-shaft type, an are being built up to 45,000 kv-a. in the vertical-shaft type.

14. Typical vertical type water-wheel generators

Location	No. of poles	Rating in kv-a.	Speed in r.p.m.	External dia. in feet	T... w... 20... (...
Cedar Rapids (Quebec)	136	10,000	556	30.5	20
Whitney (North Carolina)	28	18,000	154	19.5	16
Niagara Falls	20	32,500	150	21.5	30
Ebro (Spain)	16	14,000	375	14.5	12
Spain	10	18,750	600	14.5	15

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15. **Steam turbine-driven types.*** Extra high-speed generators are now almost invariably constructed with the cylindrical type of rotor carrying the field winding embedded in slots distributed over its surface. Owing to the great stresses associated with high peripheral speeds, the entire rotor (including the extensions constituting the shaft) is often made from a single piece of steel. In the largest machines, peripheral speeds of the order of 25,000 ft. per min. (127 meters per sec.) are employed. Bipolar 25-cycle designs are now under construction for rated loads of 40,000 kv-a. at a speed of 1,500 rev. per min. Bipolar 60-cycle designs for a speed of 3,600 rev. per min., have been built in sizes up to 9,375 kv-a.

It is characteristic of extra high-speed alternators of great capacity that since they are so exceedingly small for their output they can only be maintained at appropriately low temperatures when in operation, by circulating through them enormous quantities of air. For this purpose, and also in order to ensure reasonable absence of noise in their neighborhood, such generators are of the completely enclosed type with definite inlets and outlets for the circulating air. These subjects are discussed in Par. **129** to **139.**

ARMATURE WINDING

16. **Considerations affecting the choice of armature winding** for an alternator. (a) Efficient e.m.f. generation, *i. e.*, without considerable differential generation in series-connected conductors. This indicates coils whose pitch or span is about 180 deg. The pitch is on other accounts sometimes as low as 0.66 or even 0.50. (b) Wave shape. In most cases an approximate sine-wave is desired, which ordinarily means a distributed winding (several slots per pole per phase). It is not necessary to have a whole number of slots per pole per phase. In fact a fractional number is sometimes desirable, *e.g.*, a machine with $1\frac{1}{2}$ slots per pole per phase will have as good a wave shape, other things being equal, as a machine with five slots per pole per phase. Wave shape also usually indicates a fractional-pitch winding (Par. **20**), *i.e.*, coils with a pitch less than 180 deg. (c) From the standpoint of heat dissipation, as well as of wave shape, the winding should be distributed rather than concentrated; this also reduces the leakage reactance slightly. On the other hand, much distribution means more insulation space and less slot space for copper, particularly in high-voltage machines. (d) From the standpoint of first cost it is important that the coils shall be wound and insulated before being placed in the machines, also that they shall be of one shape rather than of many shapes. This involves the necessity of open slots, although magnetic wedges are sometimes inserted after the winding is in place, in order to secure the advantages of closed or partly closed slots.

17. **Classifications of armature windings:** (a) coil-end classification (spiral or lap; one range, two range, three range or barrel); (b) according to the number of layers (one or two); (c) according to the pitch of the coils; (d) open slots (usually with form wound coils) or closed slots; (e) according to the number of slots per pole per phase; (f) according to the number of circuits in each phase; (g) according to the number of phases; (h) in three-phase windings, *Y* or Δ connection.

Diagrammatic illustrations of three-phase windings are shown in Fig. 14 which explains itself. All of these illustrations are for **single-layer wind-**

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Shepherd, J. "Failures of Turbo-generators and Suggestions for Improvements," read before the Institution of Elec. Engrs. in January, 1920.

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ings, such that they can be wound with one coil-side per slot. It will be observed also that, in effect, they are all **full-pitch windings**, *i.e.*, that the two groups of active conductors belonging to any given phase and lying under adjacent poles are always 180 deg. apart, as groups, although some individual coils of the spiral windings have a pitch less than 180 deg.

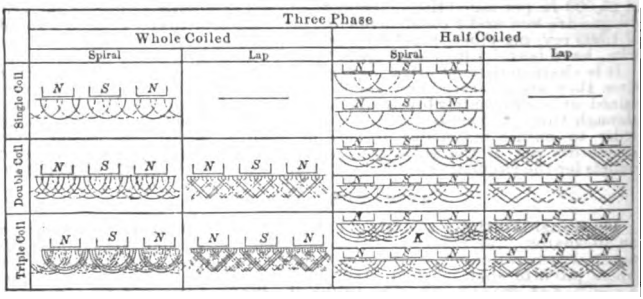


FIG. 14.—Three-phase windings.

18. A three-phase spiral winding with three slots per pole per phase is shown in Fig. 15, and a two-phase spiral winding with six slots per pole per phase in Fig. 16. For obvious reasons these are sometimes called **chain windings.** They are also **two-range windings**, *i.e.*, the coils extend outward in two ranges, or rows. Fig. 5 shows part of a **three-range winding.**

19. Two-layer lap winding. A more common type than any of the windings mentioned in Par. **18**, is the two-layer lap winding, shown in Fig. 17. This type has the advantage not only of a single shape of coil, but also that the coil pitch may be any whole number of slots, without disturbing the symmetry of the winding.



FIG. 15.—Three-phase, spiral, two-range winding.

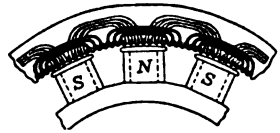


FIG. 16.—Quarter-phase, spiral, two-range winding.

20. Fractional-pitch winding. When the coil pitch is less than 180 deg., the winding is called a fractional-pitch winding. Fractional-pitch windings are much used not only because of their effect on the wave shape (Par. **25 et** seq.), but also because of the saving in coil-end copper and in over-all length of machine. The gain is particularly noticeable on two-pole machines where fractional pitch is practically universal. It is also possible with this type of winding to have a fractional number of slots per pole, which tends to eliminate tooth harmonics from the e.m.f. wave. The end connections of the two-layer lap winding stand out in a single range, but because of its appearance and continuity it is often called a **barrel winding.** Figs. 17 and 18 show samples of three-phase, two-layer lap windings with full pitch and 50 per cent. pitch respectively. The between-coil connections and phase terminals, are shown for only one phase. All things considered, the two-layer lap winding is the most flexible and generally useful type. In very high-voltage machines, the necessity for insulation between the two layers is an objection, particularly with fractional pitch, when there is a relatively large potential difference between the two coil-sides in a slot.

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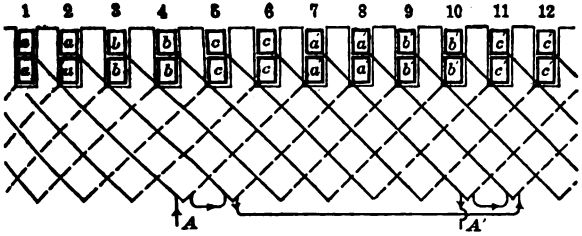


FIG. 17.—Three-phase two-layer lap winding with full pitch (*i.e.*, coil pitch $\frac{6}{6} = 1.00$), Two poles. Six slots per pole.

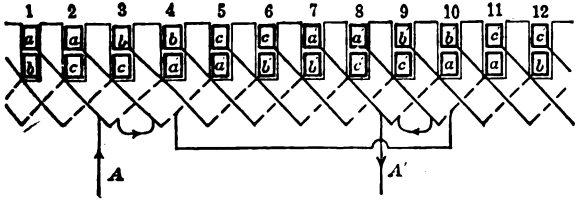


FIG. 18.—Three-phase two-layer lap winding with five-tenths pitch (*i.e.*, coil pitch $\frac{3}{6} = .50$), Two poles. Six slots per pole.

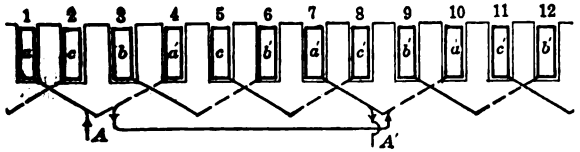


FIG. 19.—Three-phase single-layer lap winding with five-tenths pitch (*i.e.*, coil pitch $\frac{3}{6} = .50$), Two poles. Six slots per pole.

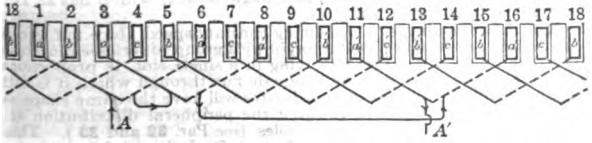


FIG. 20.—Three-phase single-layer lap winding with five-ninths pitch (*i.e.*, coil pitch $\frac{5}{9} = .556$), Two poles. Nine slots per pole.

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21. Fractional pitch single-layer lap winding. It is also possible to have fractional-pitch coils with a one-layer lap winding, but here the number of combinations is quite limited, see Figs. 19 and 20. Inter-coil connections are shown for only one phase. Fractional-pitch one-layer polyphase windings have the serious fault that in a certain portion of the slots, the phases alternate with one another, causing a very unfavorable distribution of the m.m.f. of armature reaction. Thus with three phases *A*, *B*, and *C*, four slots per pole per phase, and 75 per cent. pitch, the distribution of the phases in successive slots is as follows: *ACAABABBCBCCACAABABB*, etc. When each slot contains conductors of only one phase, the m.m.f. distribution is very unfavorable, but with a two-layer winding with four slots per pole per phase, and the same coil pitch, we obtain the following arrangement:

$$\left\{\begin{matrix} AAAABBBCCCCAA \\ CCCAAAABBBCCC \end{matrix}\right\} \text{etc.}$$

This arrangement provides a nearly sinusoidal distribution of the m.m.f.

22. Multi-circuit windings. Another classification of windings is according to the number of similar circuits in each phase; *e.g.*, a two-circuit 220-volt alternator could be changed to a single circuit 440-volt machine by series-connecting the two parallel circuits. In three-phase alternators there is still another distinction, namely, between *Y* and Δ connection of the three phases.

E.M.F. GENERATION

23. Electromagnetic induction. The law of electromagnetically induced e.m.f. may be stated in two ways: (a) whenever a conductor cuts a magnetic flux, an e.m.f. is induced which is proportional to the rate of cutting, *i.e.*, to the flux cut per sec.; (b) whenever the flux linked with a loop or coil of wire, changes for any reason, an e.m.f. is induced in the loop or coil, proportional to the rate of change of the flux and to the number of turns in the coil. For all ordinary cases, statements (a) and (b) are exactly equivalent, but for alternator electromotive forces, (a) will ordinarily be more convenient.

24. E.m.f. formulæ. Let l = gross length of armature core, inches. v = peripheral velocity in ft. per sec. $\mathfrak{B}_1$ = maximum gap density (maxwells per sq. in.) of equivalent sine-wave. e'' = root-mean-square volts per in. of active conductor. N = series-connected active conductors per phase (twice the number of turns per phase). E = volts per phase. k_b and k_p are the differential factors, Par. **28** and **29**. Then

$$e'' = \frac{12}{\sqrt{2}} v\mathfrak{B}_1 10^{-8} = 8.5 v\mathfrak{B}_1 10^{-8} \qquad \text{(volts)} \qquad (1)$$

and

$$E = k_b k_p e'' Nl = 8.5 k_b k_p v\mathfrak{B}_1 Nl 10^{-8} \qquad \text{(volts)} \qquad (2)$$

Another very common variety of the e.m.f. formula is obtained as follows: let Φ = flux per pole in maxwells; then the average e.m.f. per active conductor is $2f\Phi 10^{-8}$, and neglecting differential action, the average e.m.f. per phase is $2f\Phi N 10^{-8}$. To obtain the root-mean-square volts and at the same time to take account of the differential action, involves the form factor (k_f = ratio of root-mean-square to average volts), and the differential factors, giving for the induced volts

$$E = 2k_f k_b k_p f\Phi N 10^{-8} \qquad (3)$$

The three k's are usually combined in a single term K which has an average value of 1.05 for full-pitch windings.

25. E.m.f. wave shape. * Assuming constant speed, the e.m.f. generated by a single active armature conductor, or by a group of series-connected conductors making up a coil side and lying in a single slot, is proportional at each instant to the density of the magnetic flux through which it is cutting, and when plotted in rectangular coordinates will have the same shape as the "**field form**," *i.e.*, the curve showing the peripheral distribution of flux entering the armature from the field poles (see Par. **22** and **23**). This will be referred to as the elementary or slot e.m.f. It is an alternating e.m.f.

* See also S. P. Smith and R. S. H. Boulding, "The Shape of the Pressure Wave in Electrical Machinery," *Journal* Inst. Elec. Engrs., Vol. 53 (1915), p. 205.

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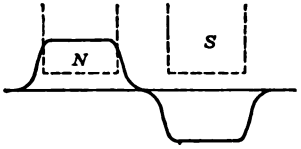


FIG. 21.—Elementary field form.

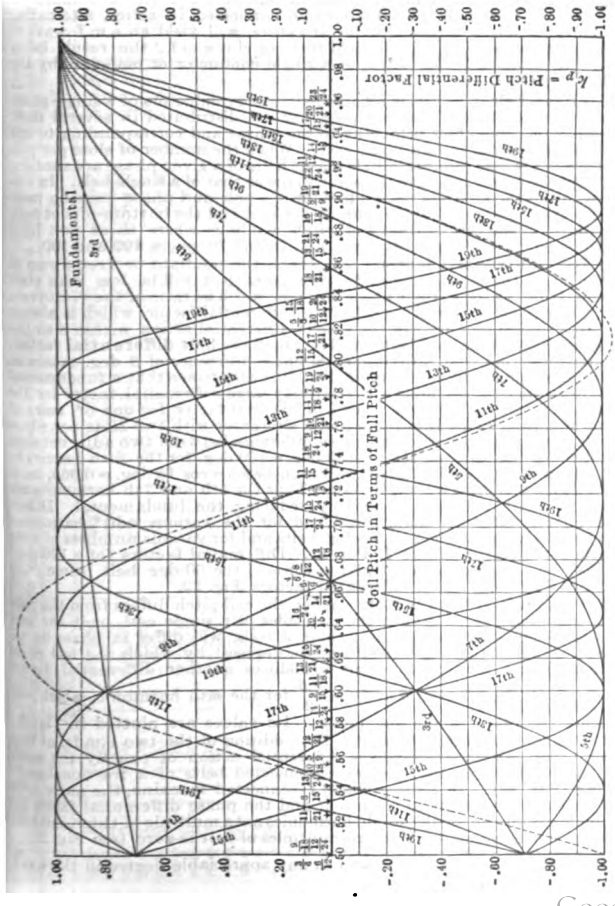


FIG. 22.—Curves of pitch differential factors.

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but usually not sinusoidal, see Fig. 21. The no-load wave-shape of the machine is then obtained by adding together the e.m.fs. of the series-connected coil sides. This is very tedious as it involves the point-by-point addition of several dephased non-sinusoidal waves. An approximation of some kind is usually employed. The most satisfactory method of handling this problem is as follows: Analyse the field form or slot e.m.f. into its fundamental and harmonics; compound or add vectorially in their proper phase relation, the fundamentals of the several series-connected conductors or coil-sides, to obtain the fundamental of the resultant e.m.f.; and compound similarly the harmonics of each order to obtain the resultant harmonic of that order. To this end the armature conductors are grouped as follows.

26. Similars. Any number of conductors or coil sides, 180 magnetic degrees apart (generally called similars), connected in series, alternating right and left across the face of the armature, will yield an e.m.f. wave of the same shape as that of the field form or slot e.m.f., the result being simply the product of the e.m.f. of a single conductor or coil-side, by the number in series.

27. Phase-belt. In nearly all alternators the conductors of a single phase are not confined to one slot per pole, but are distributed in several slots. The group of conductors belonging to one phase and corresponding to one pole, will be referred to as a phase belt. When the number of slots per pole per phase is a whole number, all the phase belts of a given phase are similars, and the phase e.m.f. will have the same shape as that of a single belt. In a 2-layer winding the group of conductors for one pole and phase may be more conveniently separated into the top-of-slot belt and the bottom-of-slot belt, particularly in the case of fractional pitch windings where these two belts are displaced circumferentially. See Fig. 78 and 79, pages 499 and 500.

28. Belt differential factor. In general the resultant or vector sum of the e.m.fs. of the several coil-sides in a given belt will be less than their numerical sum, owing to their phase differences. The ratio of the vector sum to the numerical sum will be called the differential factor, which is always equal to or less than one. In the case of differential action within a single phase belt, the differential factor will be called the **belt differential factor** k_b. Remembering that a fundamental phase difference of β deg. means an nth harmonic phase difference of $n\beta$ deg., it is easy to see that a fundamental phase difference which affords a relatively large differential factor for the fundamental, may give a very small differential factor for one or more of the harmonics. Thus, in a three-phase alternator with two slots per phase per pole, or six slots per pole, the phase difference between two adjacent slots is 30 deg. for the fundamental, 5×30 deg. $= 150$ deg. for the fifth harmonic, etc. The belt differential factors will then be $k_{b1} = \cos 15$ deg. $= 0.966$, $k_{b5} = \cos 75$ deg. $= 0.259$, $k_{b7} = -0.259$, etc. Thus the 5th and 7th harmonics are greatly reduced without appreciably reducing the fundamental. Differential factors for the fundamental and for the various odd* harmonics up to the 27th, for 60-deg. and 90-deg. belts and for various numbers of slots per pole are given in Table I, Par. 31. Differential factors for a 120-deg. belt may be obtained by multiplying those of the 60-deg. belt (same N_s) by the 66⅔ per cent. pitch differential factors, Fig. 22.

29. Pitch differential factor. When the coil pitch differs from the pole pitch, the e.m.fs. developed in the two sides of a single coil, or in the two series-connected belts of a phase-group of coils, will differ in phase by an angle β, which is the angle (in magnetic degrees) by which the coil pitch differs from the pole pitch. This introduces another differential factor $\left(\cos \frac{\beta}{2}\right)$ for the fundamental and $\cos \frac{m\beta}{2}$ for the mth harmonic, which will be called the pitch differential factor. Its values are plotted in Fig. 2

30. Phase differential factor. The addition of the two e.m.fs. of two phases of an alternator, involves differential action of exactly the same kind as that between the two series-connected belts of a fractional-pitch winding (Par. 29). In a three-phase Y-connected machine, the angle is 60 deg., which is equivalent to a ⅔ pitch; and the phase differential factor for the fundamental and for all the odd harmonics not a multiple of three, is 0.86, while for the harmonics which are multiples of 3, it is zero (see Fig. 22).

* Even harmonics are not present in any appreciable degree in the e.m. waves of commercial alternators.

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31. Belt differential factors for the fundamentals and for the different odd harmonics up to the 27th corresponding to various numbers of slots per pole (N_{sp}). 60-deg.-belt—3-phase

N_{sp} =	3	6	9	12	15	18	21	24	∞
m = 1	1.00	+0.966	+0.960	+0.958	+0.957	+0.956	+0.956	+0.956	+0.955
m = 3	1.00	+0.707	+0.667	+0.653	+0.647	+0.644	+0.642	+0.641	+0.637
m = 5	1.00	+0.259	+0.218	+0.205	+0.200	+0.197	+0.196	+0.194	+0.191
m = 7	1.00	−0.259	−0.177	−0.157	−0.149	−0.145	−0.143	−0.141	−0.136
m = 9	1.00	−0.707	−0.333	−0.270	−0.248	−0.236	−0.229	−0.225	−0.212
m = 11	1.00	−0.966	−0.177	−0.128	−0.109	−0.102	−0.097	−0.095	−0.087
m = 13	1.00	−0.966	+0.218	+0.128	+0.102	+0.091	+0.086	+0.083	+0.073
m = 15	1.00	−0.707	+0.667	+0.270	+0.200	+0.173	+0.159	+0.149	+0.127
m = 17	1.00	−0.259	+0.960	+0.157	+0.102	+0.084	+0.075	+0.070	+0.056
m = 19	1.00	+0.259	+0.960	−0.205	−0.109	−0.084	−0.072	−0.066	−0.050
m = 21	1.00	+0.707	+0.667	−0.653	−0.248	−0.173	−0.147	−0.127	−0.091
m = 23	1.00	+0.966	+0.218	−0.958	−0.149	−0.091	−0.072	−0.063	−0.041
m = 25	1.00	+0.966	−0.177	−0.958	+0.200	+0.102	+0.075	+0.063	+0.038
m = 27	1.00	+0.707	−0.333	−0.653	+0.647	+0.236	+0.159	+0.127	+0.071

90-deg. belt—2-phase or quarter-phase

N_{sp} =	2	4	6	8	10	12	14	16	∞
m = 1	1.00	+0.924	+0.910	+0.906	+0.905	+0.904	+0.902	+0.902	+0.902
m = 3	1.00	+0.383	+0.333	+0.318	+0.312	+0.308	+0.306	+0.304	+0.301
m = 5	1.00	−0.383	−0.244	−0.212	−0.200	−0.194	−0.190	−0.188	−0.180
m = 7	1.00	−0.924	−0.244	−0.180	−0.159	−0.149	−0.143	−0.139	−0.129
m = 9	1.00	−0.924	+0.333	+0.180	+0.143	+0.128	+0.119	+0.114	+0.100
m = 11	1.00	−0.383	+0.922	+0.212	+0.143	+0.119	+0.107	+0.100	+0.082
m = 13	1.00	+0.383	+0.922	−0.318	−0.159	−0.119	−0.102	−0.092	−0.070
m = 15	1.00	+0.924	+0.333	−0.906	−0.200	−0.128	−0.102	−0.089	−0.060
m = 17	1.00	+0.924	−0.244	−0.906	+0.312	+0.149	+0.107	+0.089	+0.053
m = 19	1.00	+0.383	−0.244	−0.318	+0.905	+0.194	+0.119	+0.092	+0.047
m = 21	1.00	−0.383	+0.333	+0.212	+0.905	−0.308	−0.143	−0.100	−0.043
m = 23	1.00	−0.924	+0.922	+0.180	+0.312	−0.904	−0.190	−0.114	−0.039
m = 25	1.00	−0.924	+0.922	−0.180	−0.200	−0.904	+0.306	+0.139	+0.036
m = 27	1.00	−0.383	+0.333	−0.212	−0.159	−0.308	+0.906	+0.188	+0.033

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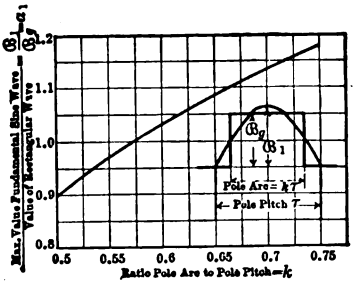


FIG. 23.

By a suitable combination of belt, pitch, and phase-differential action, any harmonics present in the field form may be practically ironed out of the terminal e.m.f. leaving only a sine-wave which is the resultant of the fundamentals of the e.m.fs. in all the series connected conductors.

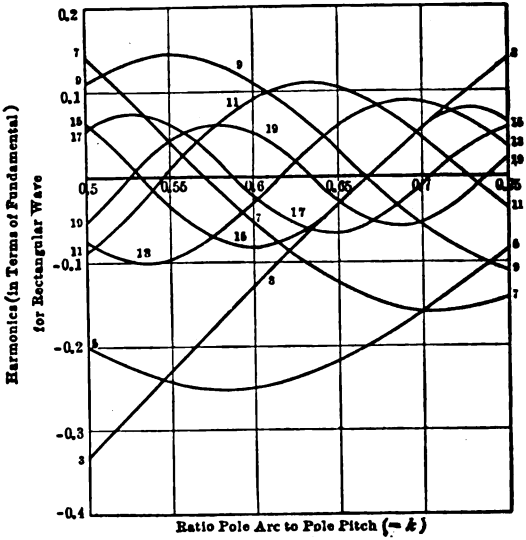


FIG. 24.—Harmonics of rectangular field forms (in terms of fundamental) plotted as a function of ratio of pole arc to pitch.

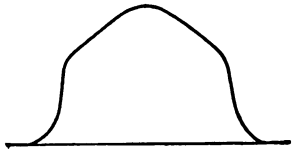


FIG. 25.—Observed field form.



FIG. 26.—Observed field form.

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32. Field form of salient-pole alternators. Neglecting the fringing of flux at the pole corners and assuming a uniform air-gap under all parts of the pole, the field form will be rectangular (see Fig. 23). The fundamental sine-wave of this field form has a maximum value: $\mathfrak{B}_1 = 1.27 \cos \pi/2\,(1-k)\,\mathfrak{B}_g = a_1\mathfrak{B}_g$. Values of a_1 for various values of k are given in Fig. 23. Fringing at the pole face edges will increase a_1 and chamfering the pole face will decrease a_1 slightly, $\mathfrak{B}_g$ being the actual gap density at the centre of the pole face.

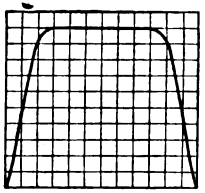
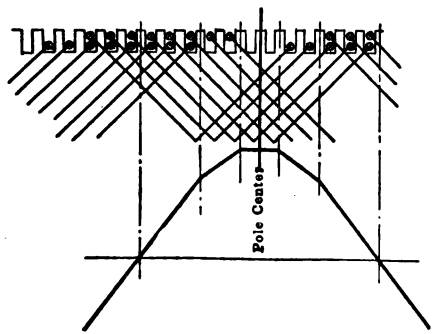


FIG. 27.—Observed field form.

Fig. 24 gives the harmonics (up to the 19th) of these rectangular field forms, plotted against k, in terms of the fundamental. The fringing will in most cases eliminate the higher of these harmonics, and considerably change the magnitude of the lower ones, usually reducing them. Thus Fig. 24 gives only a rough idea of the upper limits of the lower harmonics in the case of a uniform air-gap. If the pole face is shaped, these values may be still farther reduced. Three actual and quite different field forms are shown in Figs. 25, 26 and 27, and their harmonic analyses given below:

	Fundamental	3rd	5th	7th	9th	11th	13th	15th	17th	19th
Fig. 25.	100	+1.7	−1.5	−6.0	−4.2					
Fig. 26.	100	+2.46	−8.8	−1.31	+2.46	+0.1	−1.4	0	+0.8	0
Fig. 27.	100	+20.6	+2.8	−0.3	−1.9	−0.8	0	0	0	−0.1

33. Field form of distributed-field windings. With distributed-field windings, the field form may be more easily controlled. Fig. 28 shows



FIGS. 28 and 29.—Distributed field winding with resulting field form, effect of slots neglected. (This is for a two-layer lap winding with 5/6 pitch.)

a two-layer distributed field winding with the top-slot layer displaced 2 slots from the bottom-slot layer. This is a simple lap-winding with a 120-deg. belt, a ⅚ pitch, and 12 slots per pole. The empty slots at the centre of each pole could be filled with iron if desired. Neglecting the effect of slot openings and assuming that the current is distributed uniformly

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over each belt, the magnetic potential differences (ampere-turns) across the air gap, and therefore the field form, is shown in Fig. 29.

A simple manner in which to obtain the equivalent sine-wave of such a field form is as follows: Any such distributed field winding may be considered as made up of pairs of conductors, the two in each pair being 180 deg. apart. Consider the m.m.f. of a single pair. The field form of the pair if acting alone will be a rectangle, Fig. 30, of which the fundamental sine-wave has a maximum value, $A_1 = 4A \div \pi$. The 3rd harmonic has $\frac{1}{3}$ of this amplitude, the 5th, $\frac{1}{5}$, etc. Assuming that the resultant of the overlapping rectangular m.m.f. and flux distributions of the several pairs of conductors into which the winding has been artificially subdivided, is a curve whose harmonics are small and easily ironed out of the e.m.f. by the differential actions of the winding (*i.e.*, assuming a final sine-wave of e.m.f.); it is obviously unnecessary to consider anything but the *fundamental* of each rectangular field

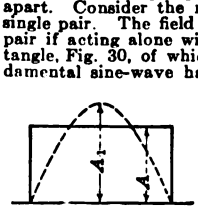


FIG. 30.—Field form of single 180-deg. loop, with its fundamental.

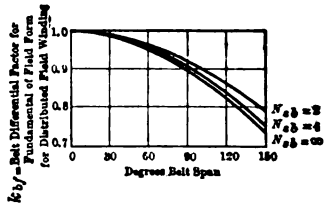


FIG. 31.—Belt differential factor for m.m.f. of distributed field windings. (N_{sb} = No. of slots per belt.)

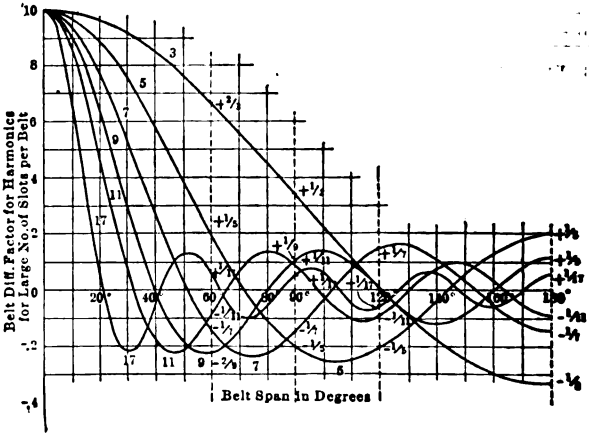


FIG. 32.—Curves of belt differential factors for harmonics plotted against belt span.

form (Fig. 30), and to compound or add together the various fundamentals which can be done geometrically, exactly as with the fundamentals of the e.m.fs. in the several conductors. It is thus possible to use the same differential factors as for the e m.fs., except that the belt of conductors or of pairs of conductors is no longer confined to the definite widths of 60 deg., 90 deg., or 120 deg., although usually within these l mits. The belt differential factor k_{b1} for the fundamental, is given, in Fig. 31 for various number

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of slots per belt, plotted against the belt span in degrees. Fig. 32 gives the belt differential factor of the harmonics for the case of a large number of slots per belt.

If Ni_b = the ampere-turns per belt, or per pole, and if K_2 = ratio of gap ampere-turns to the total (including ampere-turns in the iron part of the circuit), the ampere-turns consumed in the single gap at the crest of the wave of magnetic p.d. across the gap is

$$Ni_g = \frac{2}{\pi} k_b k_p K_2 N i_b \qquad \text{(amp-turns)} \qquad (4)$$

where k_b is from Fig. 31 and k_p from Fig. 22.

If δ be the air gap (inches) and K_1 the contraction factor due to slot opening, (Par. 40), the crest value of the equivalent sine-wave of gap flux density is

$$\mathfrak{G}_1 = 3.2\, K_1 N i_g \div \delta = 2.03\, k_b k_p K_1 K_2 N i_b \qquad (5)$$

It is thus possible to produce a substantially sinusoidal distribution of magnetic potential difference across the gap, and therefore of flux density in the gap, when the gap is uniform. If the teeth are highly saturated the field form will be flattened somewhat as compared with the m.m.f. curve.

34. Tooth kinks. The field forms of Figs. 21, 25, 26, 27 and 29, are drawn as if there were no slot openings. Strictly speaking, they are therefore, the equivalent smooth-core field forms, but are usually referred to simply as the field form. The presence of slot openings introduces flux pulsations, and kinks in the slot e.m.f. If there are 12 slots per pair of poles, there will result an eleventh and a thirteenth harmonic; if 24 slots, a 23rd and 25th harmonic, etc.

In machines with a few large slots these tooth kinks sometimes dominate the wave shape. They may be largely eliminated by the choice of a fractional number of slots per pole, so that the kinks will occur in different directions in different parts of the winding at the same instant. Sometimes this end is accomplished by the addition of one dead slot. The extra slot is then called a hunting slot. An uneven spacing of the poles accomplishes the same end in the same manner. In machines with a large number of slots per pole, small slot openings and a relatively long air gap, the presence of tooth kinks is not noticeable.

THE MAGNETIC CIRCUIT

35. Calculation of no-load saturation curve. The saturation curve, or curve of terminal voltage at no-load, plotted against field ampere-turns, can

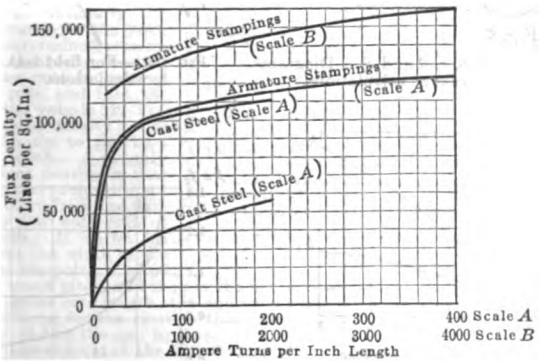


FIG. 33.—Magnetization curves of average good iron and steel.

be computed ordinarily to within about 5 per cent., provided magnetization curves of the iron in the magnetic circuit are given. If these curves are not known for the particular iron, some such curves must be used as are shown in Fig. 33. Also see Sec. 4. A fairly rough approximation to the magnetic

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qualities of the iron may not seriously affect the saturation curve, unless very high densities are used, provided the reluctance of the iron portion is small as compared with the air-gap reluctance.

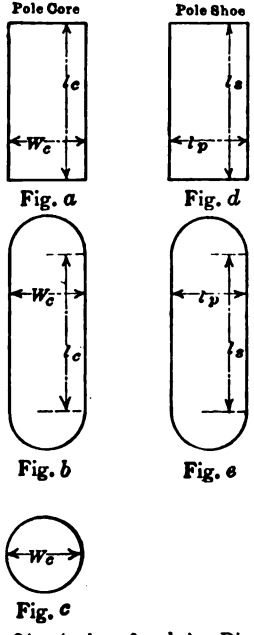


FIG. 34.—(*a*, *b*, *c*, *d* and *e*).—Diagrams for field leakage calculations.

The reluctance of the magnetic circuit is ordinarily divided into five parts, air-gap, armature teeth, armature core, pole core, and yoke. For a given no-load terminal voltage (E), the flux per pole (Φ) entering the armature, is determined by the equation $\Phi = (E \times 10^8)/(2k_f k_b k_p f N)$. See Par. **24**. To obtain the flux Φ_c in the pole core, the field leakage must be added, or Φ must be multiplied by the leakage coefficient ν.

36. Field leakage between salient poles. The leakage coefficient (ν) for salient poles is defined as the ratio of the maximum flux (Φ_c) in the pole core, to the flux (Φ) entering the armature from one pole. The difference between them is the leakage flux (Φ_l).

$$\Phi_c = \Phi + \Phi_l \text{ and } \nu = \Phi_c/\Phi = (\Phi + \Phi_l)/\Phi = 1 + (\Phi_l/\Phi)$$

This leakage flux can be divided into two parts, that (Φ_{ls}) which leaks be-

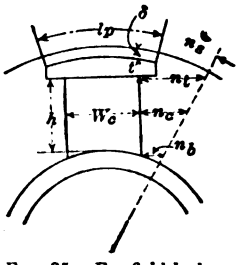


FIG. 35.—For field leakage calculations.

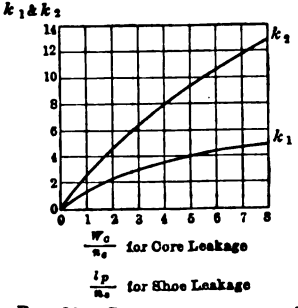


FIG. 36.—Curves of constants k_1 and k_2 employed in field leakage calculations.

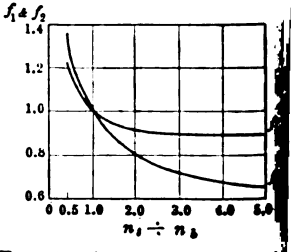


FIG. 37.—Curves of constants f_1 and f_2 employed in field leakage calculations.

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tween the pole core and the cores of the adjacent poles, and that (Φ_{l_2}) which leaks between the pole shoe and the shoes on the adjacent poles. Below are given formulæ for calculating Φ_l, the total leakage flux from one pole, for rectangular (Fig. 34a), straight-sided with semicircular ends (Fig. 34b), and circular pole cores (Fig. 34c); and for rectangular (Fig. 34d), and straight-sided with semicircular ended pole shoes (Fig. 34e). Formulæ are given for both non-stepped (that is parallel-sided) field coils, and for stepped or tapering field coils. The notation is obvious from Fig. 35. NI = the ampere-turns on one pole consumed in the gap, teeth and armature. The constants k, k_1, f_1, and f_2 are given in Figs. 36 and 37.

37. Core leakage flux.

Rectangular (Fig. 34a)	$\Phi_{l_c} = (NI/1.59)h[(2l_c/n_c)+k_1]f_1$ for non-stepped coils. $\Phi_{l_c} = (NI/1.59)h[(2l_c/n_c)+k_1]f_2$ for stepped coils.
Straight-sided with semicircular ends (Fig. 34b)	$\Phi_{l_c} = (NI/1.59)h[(2l_c/n_c)+k_2]f_1$ for non-stepped coils. $\Phi_{l_c} = (NI/1.59)h[(2l_c/n_c)+k_2]f_2$ for stepped coils.
Circular (Fig. 34c)	$\Phi_{l_c} = (NI/1.59)hk_3f_1$ for non-stepped coils. $\Phi_{l_c} = (NI/1.59)hk_3f_2$ for stepped coils.

38. Shoe leakage flux.

Rectangular (Fig. 34d) $\Phi_{l_s} = 1.255NI(t+\delta)[(2l_s/n_s)+k_1]$

Straight-sided with semicircular ends (Fig. 34e) $\Phi_{l_s} = 1.255NI(t+\delta)[(2l_s/n_s)+k_2]$

If $\Phi_l = \Phi_{l_c} + \Phi_{l_s}$ and Φ is the useful flux per pole, the leakage coefficient is $(\Phi+\Phi_l)/\Phi = \nu$. If NI corresponds to Φ at no-load, ν is the no-load leakage coefficient ν_0; if at full-load, ν is the full-load leakage coefficient, as explained in Par. 41.

39. Flux densities in the iron, and required ampere-turns. Dividing Φ_c by the cross-section of the pole-core, the flux density is obtained. The necessary ampere-turns to drive the flux through the pole are determined by finding from some such curve as that in Fig. 33, the ampere-turns per in. necessary for this density, and multiplying by the length of the pole core. Similarly the ampere-turns for the yoke may be determined, remembering that only one-half the yoke path is charged to one pole, and that the flux in the yoke is ($\Phi_c/2$).

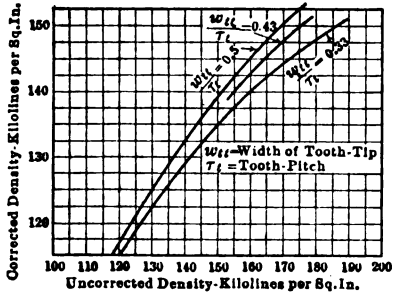


FIG. 38.—Curves for obtaining the corrected tooth density.

The tooth density varies from the tip to the root of the tooth. A roughly equivalent density is that at a point one-third of the distance from the narrow to the wide end of the tooth. If we let k_{t3} represent the width of the tooth at this point, divided by the tooth pitch, and if q_{il} is the net iron length of the armature divided by the gross core length, the equivalent density to be used in computing ampere-turns for the teeth is that found by dividing the actual maximum density ($\mathfrak{B}_g$) in the gap by $k_{t3}q_{il}$, and correcting by the curves in Fig. 38, which take account of the fact that all the flux does not enter the armature through the teeth, but that some of it passes through the slots.

The density in the armature core varies from the centre of the pole to the point midway between the poles, but a good approximation is obtained by finding the density midway between the poles ($\Phi/2$ divided by the net iron cross-section of the armature core) and estimating an equivalent

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length of path for this density. A considerable error in this item is evidently a very small part of the whole number of ampere-turns per pole.

For a non-salient pole machine the ampere-turns for the rotor can best be determined by finding the density midway between the poles, as for the armature core, and approximating to an equivalent length of path for this density. The rotor teeth may be treated exactly as the armature teeth.

A curve of terminal volts plotted against the necessary ampere-turns for the iron part of the magnetic circuit is called an **iron saturation curve.**

40. Ampere-turns for air-gap. If the armature were smooth-cored with no air-ducts, the cross-section of the air-gap would be the area of the pole face plus an allowance for fringing of the flux at the edges, and the actual density would be that determined by dividing the total flux per pole by this cross-section. This will be called the mean pole-face density. Since the flux is crowded into the teeth as it enters the armature, the density which must be used in computing the necessary ampere-turns is somewhat higher than the mean pole-face density.

The flux does not all enter the tips of the teeth, but fringes from the sides of the teeth, having the effect of increasing the width of the tooth tip (w_{tt}). This equivalent tooth-tip is given by the expression $w_{tt}+2\delta c_f$ where c_f is the fringing constant and δ the length of the air-gap. Values of c_f as a function of w_{so}/δ (the width of slot opening divided by the air-gap length) are shown in Fig. 39. If τ_t is the tooth-pitch, $a_a=(w_{tt}+2\delta c_f)/\tau_t$ is the fractional part of the tooth-pitch, which is effective as a flux path, or the fractional equivalent tooth-tip. Fig. 40 gives values of a for various values of $k_{so}=w_{so}/\delta$ and $q_{so}=w_{so}/\tau_t$.

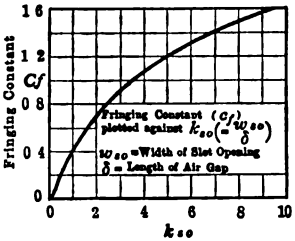


FIG. 39.—Curve for calculating air-gap reluctance.

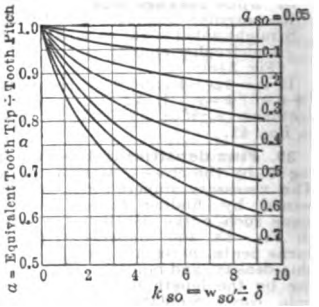


FIG. 40.—Slot contraction factor.

The peripheral-contraction factor K_1, or the ratio of effective peripheral surface to actual peripheral surface is equal to a_a for a salient-pole machine, since there is contraction only on the armature side of the air-gap. For a slot-wound field one must determine the contraction factor both for the armature (a_a) and for the field (a_f). In this case $K_1=a_a a_f$.

The equivalent length of the armature core (l_e) is given by the expression $l_e=l+\delta-N_d(w_d-2c_f\delta)$ where c_f is the fringing constant for the air-ducts, N_d = number of ducts and w_d = width of each duct. The longitudinal-contraction factor (K_d) is the fractional-equivalent armature length. It is $K_d=(l_e/l)$. The corrected gap density $\mathfrak{B}_{gc}$, upon which we must base our calculation of ampere-turns for the air-gap, is $\mathfrak{B}_{gc}=\mathfrak{B}_g/(K_1K_d)$, where $\mathfrak{B}_g$ is the mean density where the gap is shortest.

As explained in Par. **32** $\mathfrak{B}_g=\mathfrak{B}_1/a_1$, where $\mathfrak{B}_1$ is the maximum value of the equivalent fundamental sine-wave of flux under the pole, and a_1 is a constant depending upon the ratio of pole arc to pole pitch. Therefore $\mathfrak{B}_{gc}=\mathfrak{B}_g/(K_1K_d)=\mathfrak{B}_1/(a_1K_1K_d)$, and the necessary ampere-turns Ni_g for the gap are given by the equation $Ni_g=0.313\delta\mathfrak{B}_{gc}$. Adding the value of Ni_g to the number of ampere-turns per pole necessary to drive the flux through the iron parts of the magnetic circuit, we have the total number of ampere-turns per pole corresponding to the total flux Φ, and therefore corresponding to the no-load voltage with which we began. This gives, therefore, one point on the no-load saturation curve. By taking values of voltage between

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70 per cent. and 130 per cent. of the full-load terminal voltage, we shall obtain the saturation curve over a sufficient range for all calculations of regulation.

41. No-load saturation curve with full-load leakage coefficient. This may be determined as follows: In Fig. 41, curve F_o is the no-load saturation curve of the machine in question, curve $Ni_{(f+y)}$ is the m.m.f. consumed in the field core and yoke. Assume that F at full-load $= 1.4 \times F_o$ at no-load, see Par. 51. Assume also that the field leakage coefficient at no-load is $\nu_o = 1.3$. Then at full-load the leakage will be increased by 40 per cent., since it is proportional to the ampere-turns on the poles; and the full-load leakage coefficient will be $\nu_f = 1 + 0.3 \times 1.4 = 1.42$; *i.e.*, the flux in the poles and yoke has increased from 1.3 to 1.42, or 9.2 per cent. The corresponding extra m.m.f. necessary will depend upon the shape of the curve $Ni_{(f+y)}$, and is designated Ni_g in Fig. 41. Adding these extra ampere-turns to the no-load saturation curve, we obtain a point (P) on a curve of no-load volts plotted against ampere-turns for full-load leakage, or a no-load saturation curve with full-load leakage. It is obvious that a change in either phase or magnitude of the armature current will change the ratio (F/F_o), and thus the corresponding saturation curve, *i.e.*, there corresponds such a load-leakage saturation curve for each load and power-factor, see Par. 51 et seq.

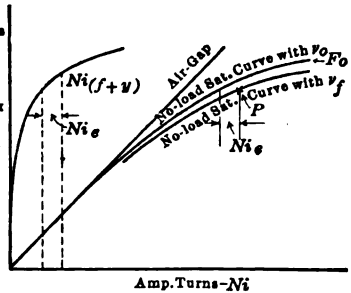


FIG. 41.—No-load saturation curve with full-load leakage, ν_f.

42. Table of average flux densities in magnetic circuit of alternators

	Frequency (cycles per sec.)	Flux density (lines per sq. in.)	
		Ordinary steel	Silicon steel
Armature core	25	60,000 to 70,000	70,000 to 80,000
	60	50,000 to 60,000	60,000 to 70,000
Armature teeth	25	100,000 to 120,000	
	60	90,000 to 110,000	
Pole core	95,000 to 110,000 lines per sq. in. for wrought-iron or steel poles.		
Yoke*	Cast steel 90,000 to 100,000 lines per sq. in.		
	Cast iron 30,000 to 35,000 lines per sq. in.		

CHARACTERISTICS OF SYNCHRONOUS ALTERNATORS

43. Regulation. The ratio of the difference between no-load and full-load terminal voltage to the latter is called the regulation, constant speed and full-load excitation assumed. Unless otherwise specified, unity power factor is assumed. The rise in voltage when the load is thrown off, or the drop when the load is applied, is chargeable to three causes: (a) armature reaction; (b) armature resistance;† (c) armature leakage reactance. See also Doherty, R. E. and Shirley, O. E., "Reactance of Synchronous Machines and Its Applications," *Trans.* A. I. E. E., Vol. XXXVII (1918), Part II, p. 1209; and Still, Alfred, "The Inherent Regulation of Synchronous Alternating-current Generators," *Jour.* I. E. E., Vol. 53 (1915), p. 587.

* The yoke density of a slow-speed machine is frequently lower than given above, as the yoke is made large in order to obtain fly-wheel effect.

† The resistance here employed should be larger (say 20 per cent.) than the ohmic resistance, to take account of the core losses due to the local or leakage flux, and eddy currents in armature conductors.

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44. Armature reaction. The magnetic p.d. across the gap due to the armature m.m.f. may be considered as made up of two parts: (a) A sinusoidally distributed p.d. stationary with respect to the field poles; and (b) pulsating kinks due to the distribution of the armature current in belts and to its localization in slots. (b) is larger, the smaller the number of phases. Neglecting (b), the maximum or crest value of this equivalent sinusoidally distributed m.m.f. is

$$A_1 = 0.45\ k_b k_p \Delta\tau \qquad \text{(amp-turns)} \qquad (6)$$

where Δ = r.m.s. ampere conductors per in. of armature periphery, τ = the pole pitch in inches; k_b = the belt differential factor, see tabulated values in Par. **31**; and k_p = the pitch differential factor, see Fig. 22.

If the field m.m.f. were also sinusoidally distributed along the air-gap, it would be an easy matter to compound or add vectorially these two m.m.fs., in order to obtain their resultant. This is nearly enough the case for alternators with distributed field windings. In the case of salient-pole machines, the m.m.f. across the gap at no-load is practically constant at all points of the pole face, but in order to simplify their treatment, the equivalent sinusoidal m.m.f. distributions will be considered. This method results in considerable errors in some cases. The crest value of this equivalent sinusoidal distribution is

$$F_1 = a_1 F_g \qquad \text{(amp-turns)} \qquad (7)$$

where a_1 (Par. **32** and **33**, Fig. 30) is about 1.27 and F_g is the constant magnetic potential difference (in ampere-turns) between armature core and pole core. With narrow or chamfered pole faces, a_1 will be slightly less. $F_g = K_2 F$, where F is the total field ampere-turns per pole and K_2 a constant varying in different machines and with different fluxes. A rough average value of K_2 is 0.8, although in extreme cases it differs considerably from this value.

Eq. (6) holds for any number of phases; but for the case of the *single-phase* alternator, the alternating armature m.m.f. must be replaced by two half-value revolving m.m.fs., one forward and one backward with respect to the armature; or one stationary and the other at double frequency with respect to the field. Eq. 6 gives only that component which is stationary with respect to the field. The other component induces double frequency e.m.fs. and currents in the field coil, and reactive e.m.fs. in the armature. (In the balanced polyphase case the backward revolving components of the several phases cancel or neutralise each other.)

45. Leakage reactance is generally supposed to represent that part of the flux linked only with the armature conductors, but as a matter of fact the only such flux is some of that linked with the coil ends, since the whole effect of the armature m.m.f. in the vicinity of the air-gap is merely to distort the main flux. However, owing to the localization of the current in slots surrounded by magnetic material which moves with the slot currents, and owing to the grouping of the slots in phase belts which move relatively to the field, there are local flux pulsations which are best treated as if separate from the main flux, although as a matter of fact they are only pulsating distortions of the latter. Armature leakage reactance of an alternator is about as difficult to define as to compute. For most practical purposes the following method will give satisfactory results.

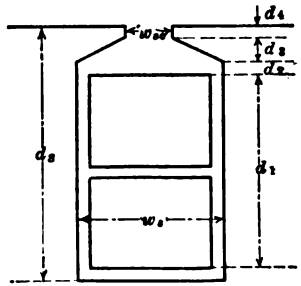


FIG. 42.—Slot section.

46. Slot leakage is the cross-slot flux, computed as if independent of the main flux. Referring to Fig. 42 the "inch permeance," or the flux linkage per amp-inch of slot, is

$$\varphi_s = 3.2\left(\tfrac{1}{3}\frac{d_1}{w_s} + \frac{d_2}{w_s} + \frac{2d_3}{w_s + w_{so}} + \frac{d_4}{w_{so}}\right) \qquad \text{(maxwells)} \qquad (8)$$

and the corresponding or slot reactance per phase is

$$x_s = 2\pi f\, k_p^2\, lN\, N_{cs}\, \varphi_s\, 10^{-8} \qquad \text{(ohms)} \qquad (9)$$

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where N_{ss} is the number of conductors per slot, l the gross core length and N the series-connected conductors per phase. The most convenient form in which to express reactance is as the *ratio of the reactance volts to the induced volts*. In this case it is—

$$q_{zs} = 0.74\varphi_s \tau_l \frac{k_p}{k_b} \frac{\Delta f}{v\mathfrak{B}_1} = 4.44 \frac{\varphi_s}{N_{sp}} \frac{k_p}{k_b} \frac{\Delta}{\mathfrak{B}_1} \quad (10)$$

where τ_l is the tooth pitch in inches, Δ the root-mean-square ampere-conductors per in. of periphery, and N_{sp} the number of slots per pole.

47. Tooth-tip leakage. This includes the flux that links with the slot conductors from tip to tip of tooth, sometimes by way of the interpolar air space, and sometimes across the air gap to pole face and back again. The effect of the presence of the pole face is usually neglected in making this calculation, since not only is the air gap long in the majority of alternators, but even were it not, the damping effect of the pole-face eddy currents would tremendously increase the apparent reluctance of the path through the iron of the pole face, with the result that it would approach the reluctance of air. In computing this flux, the integration is carried only to the centre of the tooth (see Fig. 43), since anything beyond this point would be chargeable to belt leakage. The flux linkage per ampere-inch of slot is—

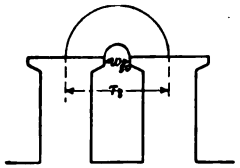


FIG. 43.—Tooth-tip leakage.

$$\varphi_{tt} = 3.2\left(0.3 + \frac{1}{\pi}\log_e \frac{\tau_l}{w_{so}}\right) = 0.96 + 2.35 \log_{10} \frac{\tau_l}{w_{so}} \quad (11)$$

and the per cent. tooth-tip reactance or *reactance ratio*, see Eq. 10, is—

$$q_{zst} = 0.74\varphi_{tt} \frac{k_p}{k_b} \frac{f\Delta}{v\mathfrak{B}_1} = 4.44 \frac{\varphi_{tt}}{N_{sp}} \frac{k_p}{k_b} \frac{\Delta}{\mathfrak{B}_1} \quad (12)$$

48. Belt leakage. This covers the belt pulsations mentioned in Par. 44 (b). It is difficult to define or to compute this effect in terms of an equivalent leakage reactance, but the following method gives fairly satisfactory results. Compute the average mutual inductive effect of all the other slots in a given belt upon a given slot, by an extension of the tooth tip integration in circular paths to the edge of the belt. This is taken as a measure of the belt leakage. The equivalent flux linkage per ampere-inch of slot, for a full-pitch winding, is roughly,

$$\varphi_b = 0.7\ (N_{sb} - 1) \quad (13)$$

where N_{sb} = number of slots per belt.

Then since $N_{sb} = N_{sp}/p^1$, where p^1 = number of phases, the *belt-reactance ratio* is—

$$q_{zb} = 4.44 \frac{\varphi_b}{N_{sb}} \frac{\Delta}{k_b\mathfrak{B}_1} = 3.3\left(\frac{1}{p^1} - \frac{1}{N_{sp}}\right) \frac{\Delta}{k_b\mathfrak{B}_1} \quad (14)$$

for full pitch winding only. The effect of changing the pitch, on this element of leakage, is very marked, but not readily computed for the general case. The pitch factor k_p, as used when the slot is the unit, cannot be employed when the belt is the unit. Certain special cases may, however, be computed. Take for example the case of a five-sixths pitch in a three-phase winding; the three belts per pole are broken up into six equal belts with a pitch differential action in each belt. For the purposes of this computation there are now six phases and q_{zb} will be reduced to considerably less than half of its full-pitch value. If $N_{sp} = 6$, q_{zb} will be reduced to zero. If $N_{sp} = 12$, q_{zb} will be reduced to one-third, and so on. For two-thirds pitch, however, the number of belts is not changed and the pitch factor k_p applies directly.

Let $\varphi_s = \varphi_s + \varphi_{tt} + \varphi_b$ be *the total flux linkage per ampere-inch of slot*, then *the total leakage reactance volts of the slot-embedded active conductors*, in terms of the induced voltage, is

$$q_{se} = 4.44 \frac{\varphi_s}{N_{sp}} \frac{k_p}{k_b} \frac{\Delta}{\mathfrak{B}_1} \quad (15)$$

and the corresponding reactance in ohms is

$$x_s = 2\pi f k_p^2 l N N_{ss} \varphi_s 10^{-8} \quad \text{(ohms)} \quad (16)$$

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For very hurried computations φ_s is sometimes approximated without computation; it varies from 8 with shallow open slots to 15 with deep nearly closed slots.

49. Coil-end leakage. This computation is simplified by the fact that φ_f, the flux per ampere-inch of outside phase-belt-bundle, is nearly a constant quantity for full-pitch windings. Its values for all pitches of working range are given in Fig. 44.

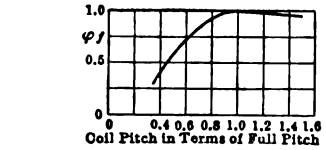


FIG. 44.—Curve of values of flux per ampere-inch for coil ends.

The coil-end reactance in ohms is then—

$$x_f = 2\pi f \varphi_f l_f \frac{N^2}{2p} 10^{-8} \quad \text{(ohms)} \quad (17)$$

where l_f = the length of a single coil end, or the free length corresponding to one active conductor, N the active conductors per phase, and $2p$ the number of poles.

The coil-end *reactance ratio* (Par. 46) is—

$$q_{xf} = 1.48\, k_f \varphi_f \frac{k_s}{k_b k_p} \frac{\Delta}{\mathfrak{G}_1} \quad (18)$$

where k_f ($= l_f/\tau$) is about 1.5 times the per cent. coil-pitch expressed as a fraction (somewhat larger for very high-voltage machines), and $k_s = \tau/l$.

50. Total leakage reactance.

$$x = x_s + x_f = 2\pi f N 10^{-8} (k_p^2 l N_{ca} \varphi_s + \frac{N}{2p} l_f \varphi_f) \quad (\text{o}_\text{h}\text{ms}) \quad (19)$$

$$q_s = q x_s + q x_f = \frac{\Delta}{\mathfrak{G}_1} \left(4.44 \frac{\varphi_s}{N_{sp}} \frac{k_p}{k_b} + \frac{1.48\, k_f}{k_b k_p} \varphi_f k_s \right) \quad (20)$$

51. Alternator vector diagram. Assume a sinusoidal peripheral distribution of m.m.f. on both armature and field and a uniform peripheral reluctance. (This assumption is warranted in non-salient pole machines, but gives rise to considerable errors in some salient pole machines.) The resultant m.m.f. and gap-flux distribution will then also be sinusoidal.

Referring to Fig. 45, designate the flux by Φ, the corresponding reluctance a.t. across gap by R_1, the armature amp-turns by A_1 (see Par. 44), and total a.t. across the gap by F_1 all sinusoidally distributed. These are all space vectors on the assumption that the field rotates counter-clockwise with respect to the armature, R_1 being the resultant of F_1 and A_1. In salient-pole machines substitute F (the full field amp. turns × 1.27) for F_1 and the corresponding R for R_1. This partly balances the error due to the unsymmetrical peripheral reluctance.

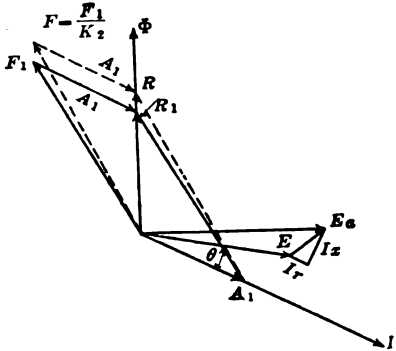


FIG. 45.—*General* alternator diagram for non-salient poles (full lines). Salient poles (broken lines).

Considering Φ as a time vector, the induced e.m.f. E_s will lag 90 deg. Subtracting Ir and Ix from E_s gives the terminal voltage E, where θ is the load phase angle. Hereinafter this diagram will be called the *general* alternator diagram.

52. Application of alternator diagram to the regulation problem. Given the winding data of armature and field, the armature resistance and leakage reactance, and the saturation curve, the excitation and regulation for any load and power-factor may be obtained as follows:

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Starting with E and I, add Ir and Ix to get E_a; from the saturation curve with full-load leakage (Figs. 41 and 46) take R; add $-A$ to get F, which is the required excitation. From the saturation curve corresponding to no-load leakage, take E_F; the regulation is then $(E_F - E)/E$. There are many variations of the above method, some of which are contained in Par. 86 to 88.

The rise of voltage when the load is thrown off is partly due to the release of the impedance voltage Iz, and partly due to the release of that part of the field m.m.f. employed in balancing the armature m.m.f., A. The first of these changes (*i.e.*, from E to E_a) is dependent wholly upon the magnitude of r and x and the power-factor of the load, r and x being assumed constant. But the change from E_a to E_F is due not only to the magnitude and phase of A but also to the degree of saturation of the magnetic circuit, *i.e.*, to the mean slope of the saturation curve between E_F and E_a.

83. Saturation factor. The degree of saturation may be expressed in terms of the saturation factor, which is defined as the ratio of a small percentage increase in excitation to the corresponding percentage increase in the flux or induced voltage. The mean saturation factor between E_a and E_F is $\overline{ob}/\overline{ab}$ (Fig. 46). Designating this by k_{sf}, $E_F = E_a F/k_{sf} R$. The saturation factor should be taken from the saturation curve for no load leakage; but for other purposes, use the saturation curve for full load leakage. (See Par. 41).

84. Short-circuit diagram and leakage reactance. The short-circuit diagram is given in Fig. 47. From this the leakage reactance may be computed as follows: From F subtract A (computed from Eq. 6) to obtain R; look up corresponding E_a on saturation curve; $z = E_a/I$ and $x = \sqrt{z^2 - r^2}$. In most cases it is sufficiently accurate to subtract A from F numerically, since they are nearly in phase, and to assume $x = z$. x may be obtained in a similar manner from the zero power-factor saturation curve, Par. 86.

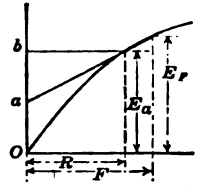


FIG. 46.—Defining saturation factor.

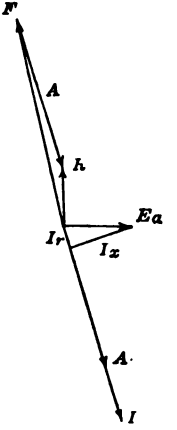


FIG. 47.—Short-circuit diagram for alternator.

In both of these cases however the results are very crude, since a small error in A means a larger error in x.

85. Load saturation curve for zero power-factor. Referring to Fig. 48, curve E_a is the no-load saturation curve with full-load field leakage, and $\overline{ob}$ is the field ampere-turns corresponding to a given armature current on short-circuit ($E = O$). From Fig. 51, $\overline{ob}$ is approximately equal to A'. $\overline{ab}$ is laid off equal to A, the armature m.m.f. Then $\overline{oa}$ approximately equals R (Figs. 47 and 51), and $\overline{ac}$ is approximately equal to Ix. If any load has zero power-factor and the same current as that assumed on short-circuit, Ix will be approximately in phase with the terminal voltage E, and at right angles to I. Thus for any point E_a on the no-load characteristic, the terminal zero power-factor voltage for the given current will be obtained by subtracting Ix vertically, and adding A horizontally. The zero power-

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factor saturation curve will then be obtained by drawing lines from [illegible] equal and parallel to $\overline{cb}$, as shown. The fact that Ir is neglected is [illegible] significant, since it is in this case at right angles to E and does not affect the result appreciably. This curve may also be determined experimentally.

56. Load saturation curves at other power-factors. If the [illegible] saturation curve at other power-factors could be obtained, it is obvious that the regulation and excitation for any power-factor and terminal voltage could be obtained directly therefrom. A semi-empirical method of obtaining these curves, recommended in the latest edition of the Standardisation Rules of the A. I. E. E. is given in Sec. 24.

57. E.m.f. method. This method practically assumes a field flux wholly dependent on the field m.m.f., as given by the saturation curve, and that all the drop is due to an internal impedance which is commonly called the **synchronous impedance**, z_s, of which the **synchronous reactance** is x_s. Fig. 49 shows saturation and short-circuit characteristics with the derived synchronous impedance curve, the ordinates of the latter being the ratios of corresponding ordinates of the other two.

58. The m.m.f. method. This method is best understood by reference to Fig. 50, where the general diagram is dotted in. Starting with E and I, add Ir to [illegible] to get E', which is assumed to be the total induced e.m.f., corresponding to [illegible] as taken from the saturation curve. From E' subtract the m.m.f. A' taken from the short-circuit characteristic corresponding to the particular current in

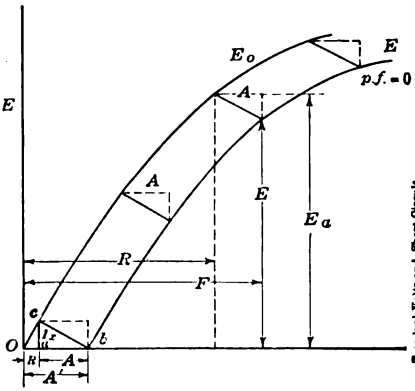


FIG. 48.—No-load saturation curve and zero-power-factor load saturation curve.

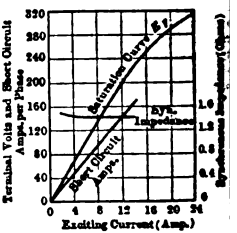


FIG. 49.—Alternator characteristic curves.

question. A' is the F of Figs. 47 and 51 and includes with the armature *m.m.f.* A, an additional *m.m.f.* $\overline{AA'}$ (Fig 50), which is practically equivalent to R of Fig. 47, and which is the approximate m.m.f. equivalent of Ix. Under short-circuit conditions, $E' = Ir$ and the diagram reduces to Fig. 51, whence it is obvious that the field ampere-turns at short-circuit practically corresponds with what we have called A'.

59. Excitation characteristics. Curves showing the relation of excitation (for constant terminal voltage) to the load current, at various power-factors, are shown in Fig. 52 for a 1,600 kv-a. slow-speed alternator with close regulation, and in Fig. 53 for a 6,250 kv-a. turbo-alternator with poor regulation. These were computed by the m.m.f. method.

60. Relation of regulation to per cent. armature strength and length of air gap. A study of Figs. 45 and 50 will show that for a given current and power-factor, the regulation depends upon the following ratios

$$Ir/E_a = q_r;\ Ix/E_a = q_x \text{(see Eq. 20)};\ \frac{A}{R} = q_A$$

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nd the saturation factor, k_{sf}; and that except for their relation to the satu-ation, a given q_x will have exactly the same effect as the same numerical

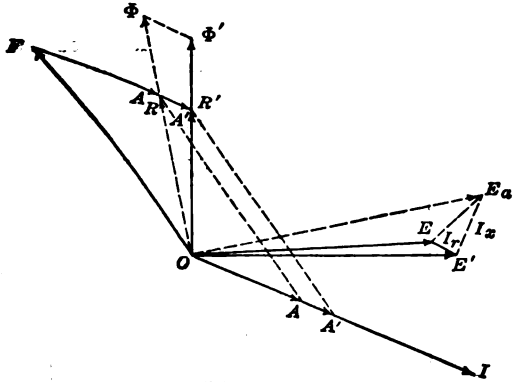


FIG. 50.—*M.m.f.* diagram (full lines) and *general* diagram (dotted lines).

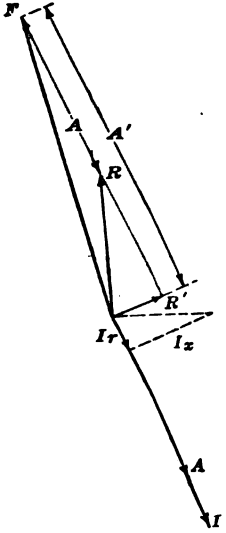


FIG. 51.—Short circuit m.m.f. diagram.

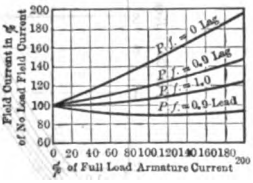


FIG. 52.—Excitation characteristic curves for a 1600-kv-a. slow-speed alternator with relatively long air gap.

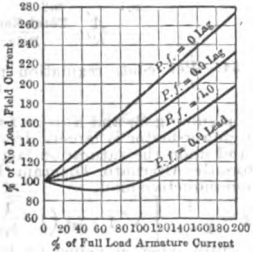


FIG. 53.—Excitation-characteristic curves for a 6,250-kv-a. turbo-alternator with relatively short air gap.

q_A. In the m.m.f. method, q_s and q_A are combined in $q = A'/R'$ (see Fig. 50) and $q = q_A + q_s$ approximately, $= A' + R'$ approx.

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Of these four ratios, q_r varies from less than 0.005, in large turbo-alternators, to 0.02 or more in small slow-speed machines; q_a from 0.04 to 0.1 or more; q_A from 1.00 to 0.35; and k_{sf} from 1.5 to 2.0. These last two are the dominant factors in regulation.

Since (approximately) $R = 0.313\mathfrak{G}_1\delta/(K_1K_dK_2)$ (see Par. 33 and 40),

$$q_A = (A/R) = (1.43k_bk_pK_1K_dK_2\Delta_T)/(\mathfrak{G}_1\delta) \quad (21)$$

or taking average values for the K's,

$$q_A = 0.9(\Delta_T)/(\mathfrak{G}_1\delta) \quad (22)$$

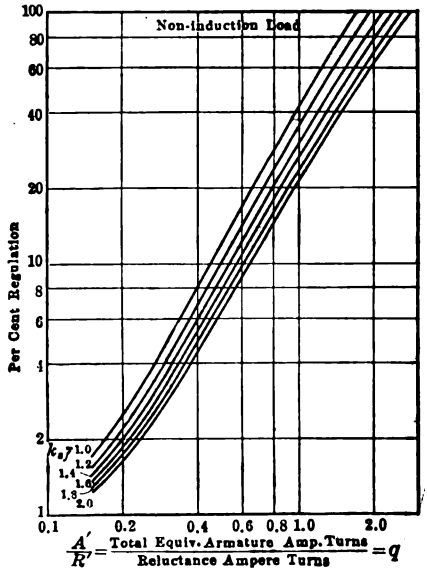


FIG. 54.—Per cent. regulation plotted in terms of per cent. armature reaction.

Thus assuming $\mathfrak{G}_1$ and Δ to be fixed for any given case, the regulation at a given power-factor is largely dependent upon the ratio of pole pitch to air gap and upon the saturation factor.

From the Alternator Diagram (Fig. 45), with some approximations we get, for non-inductive load,

$$\text{Reg.} = \frac{1}{1-q_r}\left[\sqrt{1+q_a^2}\left(1-\frac{1}{k_{sf}}\right)+\frac{\sqrt{1+q^2}}{k_{sf}}\right]-1 \text{ (roughly approx.)} \quad (23)$$

Substituting average values for large machines, $q_r = 0.005$, $q_a = 0.07$.

$$\text{Reg.} = 1.005\left(0.007+\frac{\sqrt{1+q^2}-1.0024}{k_{sf}}\right) \quad \text{(roughly appox.)} \quad (24)$$

or in terms of $q' = A' + F$;

$$\text{Reg.} = 1.005\left(0.007+\frac{1+\sqrt{1-q'^2}-1.0024}{k_{sf}}\right) \quad \text{(roughly approx.)} \quad (25)$$

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Figs. 54 and 55 are plotted from Eqs. 24 and 25. For small low-speed machines where q_r and q_s are larger than here assumed, the curves will lie a little higher at their lower ends.

Thus good regulation means large R' and long air gap, longer in proportion to Δ and τ, *i.e.*, very long for large high-speed machines such as turbo-alternators. In fact, to obtain a regulation of even 10 per cent. in large turbo-alternators would necessitate a tremendous air gap and more field copper than there is room for.

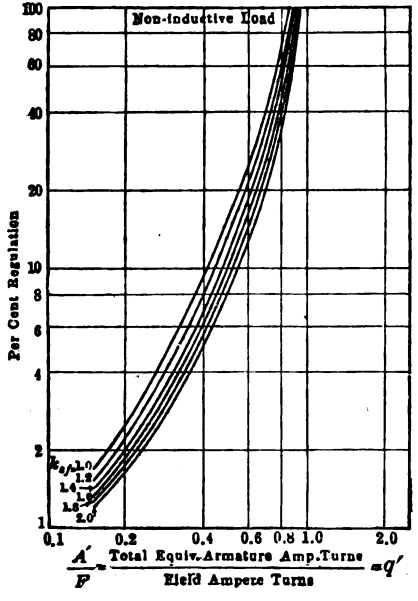


FIG. 55.—Per cent. regulation plotted as a function of $\frac{A'}{F}$.

61. Close regulation usually undesirable. With automatic voltage regulators such as now employed, close regulation is no longer necessary even in small plants. Moreover large low-reactance machines are dangerous in case of sudden short-circuits (Par. **62** to **64**). If, however, the ratio of armature ampere-turns to field amere-turns is too high, the gap flux distortion in a salient-pole machine may be sufficient to seriously distort the e.m.f wave. This does not apply with equal force to non-salient-pole machines which include most of the large high-speed alternators, where large q_A is commercially necessary.

62. Short-circuits. If the external impedance of an alternator be gradually reduced to zero, with full-load excitation and normal speed maintained, the short-circuit current, in terms of full-load current, will be $F/A' = 1 + q'$ (see Figs. 50 and 51), and correspondingly less at no-load excitation. If an alternator with a regulation of 5 per cent. and a saturation factor of 1.6, is short-circuited with full-load excitation, the short-circuit current will

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be about 3 times full-load current. At no-load excitation the short-circuit current will be 2.7 times full-load current. For an alternator with 20 per cent. regulation and a saturation factor of 1.6, the short-circuit current will be 1.56 for full-load excitation and 1.18 with no-load excitation.

63. Sudden short-circuits. Since on short-circuit, most of the field m.m.f. is consumed in balancing the armature m.m.f., the net m.m.f. and the flux are greatly reduced. If the short-circuit is applied suddenly, the sudden decrease in flux induces a large e.m.f. and current in the exciting winding which tries to keep the flux from changing, and as the electromagnetic inertia and the time constant of the combined circuits are large, an appreciable time elapses before the field is destroyed. Meanwhile the opposing m.m.fs. of armature and field rise until nearly all the field flux is shunted across between field and armature. To do this requires a m.m.f. as many times greater than that at full-load, as the full-load field flux is greater than the total full-load leakage flux (field and armature). Thus if $\nu = 1.12$ at full-load zero p.f., and $q_x = 0.10$ (salient pole slow-speed machine), the r.m.s. armature amperes will rise temporarily to nearly 5 times its full-load value, and owing to the fact that one of the phase currents will be boosted up above its zero axis, because of the position of that phase at the instant of short-circuit, the maximum instantaneous current in one phase may be nearly double the maximum value of the above r.m.s. current.

In non-salient pole turbo-alternators ν may be as low as 1.04, q_x as low as 0.04, the r.m.s. current nearly 12 times full load, and the instantaneous maximum more than 20 times normal. This means mechanical stresses on coil ends more than 400 times normal, which shows the imperative necessity of providing great strength in the design of the end connections and the means for their support.

64. Current-limiting reactances. As the total leakage $(\nu - 1 + q_x)$ should not be less than 0.15, external reactances are very often supplied to protect against sudden short-circuits. See Par. 140.

65. Rating of alternators. As the armature current, irrespective of power-factor, determines the armature copper loss, it is customary to rate alternators in kv-a. rather than in kw. In fact at low power-factors, and therefore at smaller values of delivered power, but with a given current and terminal voltage; the flux, core-loss, field current and field copper loss are all larger than at unity power-factor. Therefore the safe output is less for a given temperature rise. It is thus necessary to specify the lowest power-factor at which an alternator is expected to operate, in order that enough excitation may be provided, and the corresponding field copper loss dissipated without excessive temperature rise. The maximum safe voltage rating is that which can be maintained at rated current and power-factor with the excitation voltage available, and without exceeding approved temperature limits for the field windings.

66. Automatic voltage regulators, external to alternator. The most successful of these is the Tirrill regulator or some modification thereof. In principle it is merely a voltage-operated relay which closes a low resistance by-pass around the shunt-field rheostat of the exciter when the voltage is too low, and opens it when the voltage is too high. This relay vibrates continuously, so that the exciter-field current does not change at each contact by any considerable amount, but assumes a pulsating intermediate value depending on the percentage of time the by-pass is closed. With proper adjustment this regulator will maintain the voltage as nearly constant as is ordinarily desired in commercial power plants.

SYNCHRONOUS MOTORS

67. Structure. The synchronous motor is simply a synchronous generator with its function reversed. In structure it usually consists of a synchronous generator with the addition of pole-face windings to provide suitable starting characteristics. If an auxiliary motor is provided for starting, there is no need for the pole-face windings for starting purposes, although it is still desirable for counteracting "hunting." (See Par. 78 to 79.)

68. Diagrammatic representation. Owing to its simplicity the e.m.f. method of diagrammatic representation will be employed here, in spite of

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its considerable inaccuracy. A single-phase machine or a single phase of a polyphase machine will be considered for the sake of simplicity. Single-phase synchronous motors are, however, practically never actually employed.

69. Theory of operation. Consider a synchronous machine driven at such speed and at such excitation that its e.m.f. (E_2), in frequency and magnitude, is exactly the same as that (E_1) of the supply circuit, of which

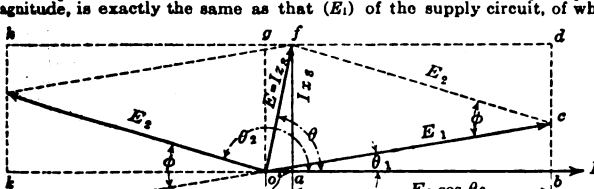


FIG. 56.—E.M.F. vector diagram of synchronous motor.

the voltage and frequency may be assumed constant. Assume also the phase of the machine voltage in exact opposition to that of the supply voltage. As these two exactly neutralize, there will be no current when the machine is connected to the supply circuit. Imagine now the driving power removed. The machine will begin to slow down; but as soon as the retardation begins, E_2 falls back (clockwise), yielding a resultant E, and a current $I = E/z_s$ (Fig. 56), where z_s is the synchronous impedance of the motor. As z_s is almost wholly synchronous reactance (the resistance being frequently not more than 5 per cent. of x_s), the current will lag almost 90 deg. behind E, and, for small values of φ, will be nearly in phase with E_1 and in opposition to E_2. Thus the power P_1 delivered by the supply circuit is $E_1 I \cos \theta_1$ (proportional to the area of the rectangle $obdg$), the power P_2 transformed into mechanical form in the motor, is $E_2 I \cos \theta_2$ (proportional to the area of rectangle $\overline{abdf}$) and their difference $P_1 - P_2 = I^2 r$ is the armature copper loss in the motor (proportional to the area of the rectangle $\overline{oafg}$). Other losses are neglected.

The power (P_2) transformed is a function of φ, the coupling angle; it is

$$P_2 = \frac{E_2^2}{z_s} \cos \theta - \frac{E_1 E_2}{z_s} \cos (\theta - \varphi) \qquad \text{(watts)} \qquad (26)$$

The significance of the negative sign is that the electrical power is negative, i.e., received instead of delivered. In Fig. 57, $-P_2$ is plotted against φ; whence it appears that as the motor lags (not in speed but in phase) behind the supply e.m.f., the output increases to a maximum, then decreases, becomes negative and returns to zero. As soon as φ has opened out to a point such that P_2 is sufficient to carry the load, it will hang at that point as if the motor were driven by an elastic coupling. If the load increases, φ will increase accordingly, until the maximum point is passed, when the motor will break down. During a little more than a half of each slip cycle (see Fig. 57), the motor is acting as a generator, since $-P_2$ is positive, and is in series short-circuit with the line. So much of the kinetic energy of momentum is lost during this half of the slip cycle that a synchronous motor does not readily pull back into step after once breaking, even if the mechanical load be immediately removed.

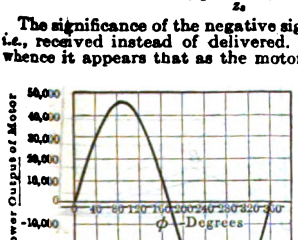


FIG. 57.—Synchronous motor output vs. coupling angle.

For visualizing these relationships and their causes the Blondel diagram is by far the simplest device.

70. Blondel diagram. Referring to Fig. 58, the isosceles triangle $\overline{OAC}$ is constructed on the base E_1 with base angles, $\theta = \tan^{-1}(x_s/r)$. It can easily be shown that with constant impressed voltage E_1, and constant load, P_2, the locus of the point B, as the excitation and E_2 vary, is a circle with centre at C and with radius $\sqrt{(E_1/2)^2 - P_2 r} + \cos\theta$. If $P_2 = O$, the radius is $(E_1 + 2\cos\theta) = \overline{CA}$, and the circle passes through O and A. As P_2 increases, the radius decreases until it becomes zero, which corresponds to the maximum possible output with the given motor at the given impressed e.m.f. But this theoretical limit is never reached practically, because of the very large value of E_2 required to reach up to the high-power circles of small radii. This will be better appreciated by reference to the diagram of Fig. 59, where the proportions are more normal and the point C is far off the page.

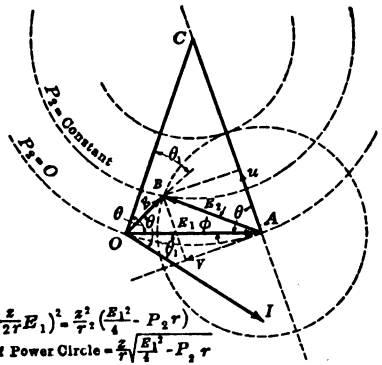


FIG. 58.—Blondel diagram for synchronous motor.

For varying load and constant excitation, B moves along a circle about A, clockwise for increasing and counter-clockwise for decreasing loads. The maximum load for any given excitation occurs when B falls on $\overline{AC}$; beyond that B swings around on to circles of smaller power, and the motor breaks down; *i.e.*, the decrease of $\cos\theta_2$ more than balances the increase in I.

71. Interpretation of Blondel diagram. In Fig. 58 the area inside of the zero-power circle corresponds to motor power, and that outside to generator power; the area to the left of $\overline{AC}$ corresponds to stable operation and that to the right to unstable operation; the area within the zero-power circle and between $\overline{AC}$ and $\overline{OC}$ corresponds to stable motor operation with a lagging current, and that to the left of $\overline{OC}$ to stable motor operation with leading current. The point B is not only the extremity of the E_2 vector, but may be used also as the outer end of the current vector, since E is proportional to I, and angle $\overline{COB} = \theta_1$. Thus when B falls on $\overline{OC}$, I is in phase with E_1 and I is a minimum for that particular load. With normal steady load conditions, the angle ϕ never approaches the angle θ, *i.e.*, the point B never approaches the breakdown point on AC (see Fig. 59); but if either the load

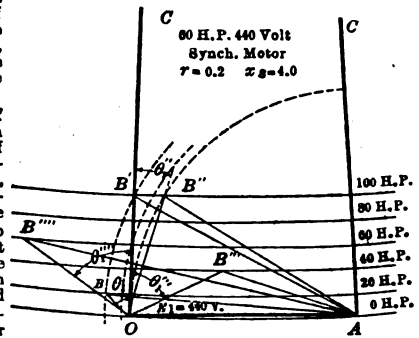


FIG. 59.—Portion of Blondel diagram drawn to scale.

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or the frequency of supply pulsates or changes suddenly, a hunting may be set up which will carry B over into the region of unstable operation.

73. Excitation and power-factor curves. The familiar "V" curves of current vs. excitation or induced e.m.f. may be easily obtained from the Blondel diagram. This has been done for a 60-h.p. motor, and the result is shown in Fig. 60. Power-factor curves similarly obtained, are shown in Fig. 61.

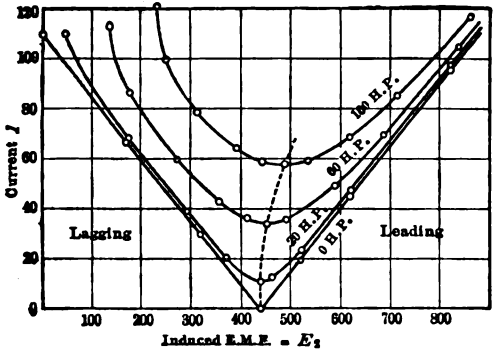


FIG. 60.—V-curves for 60-h.p. synchronous motor.

73. Synchronizing power. By this is meant the stiffness of the coupling or the change in power absorbed per degree change of the coupling angle ϕ, it increases with the air gap and inversely as $q'(=A'/F)$. See Par. 60.

74. Hunting of synchronous motors. Owing to the elastic nature of the electromagnetic motor coupling, any impulse will tend to set up an

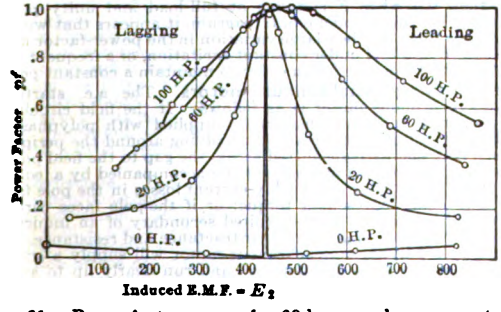


FIG. 61.—Power-factor curves for 60-h.p. synchronous motor.

oscillation about the position of equilibrium, which will continue until the energy by which it was initiated, is absorbed by the extra losses incident to the oscillation. Such oscillation is called hunting, and the absorption of the energy of oscillation is called damping.

75. Hunting may be instigated either by a temporary disturbance, such as a sudden change of load on the motor or of the frequency of supply,

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or by some periodic disturbance (Par. 76) such as the pulsation of impressed frequency set up by the prime mover. This periodic disturbance may be one of comparatively high frequency due to the pulsation of the crank effort of a reciprocating steam or gas engine during each revolution, or one of comparatively low frequency due to the hunting of the governor of the prime mover.

76. Frequency of hunting. If the period of the impressed disturbance be approximately equal to that of the natural oscillation of the motor, there will obviously be a tendency for the motor to hunt with increasing amplitude, which may result in a complete breakdown or pulling out of step. A periodic pulsation in the load on the motor may also produce the same result, although such is much less common. It is thus important to know what is the natural frequency of oscillation of a synchronous motor, and upon what factors it depends.

The natural hunting frequency is approximately

$$f_h = 0.422\, E_1 \sqrt{\frac{pp'}{J z_s}} \text{ rev. per. min.} \qquad (27)$$

where J is the moment of inertia in *lb. ft.*^{2} and p' the number of phases.

The z_s used in Eq. 27 should be the combined impedence of alternator, line and motor. The smaller the motor as compared to line and alternator, the less will be the effect of line and alternator impedence upon the hunting period of the motor.

77. Dampers. Forced hunting may be considerably reduced and temporary oscillations more quickly damped out, by means of field dampers, consisting of : (a) a copper loop around each pole face; (b) a copper bridge between poles; or, better still, (c) a squirrel-cage set of copper conductors through the pole face with end rings. These dampers tend to check pulsations of the pole-face flux due to the pulsating armature *m.m.f.*, by induced currents which absorb the energy of oscillation.

78. Length of air-gap. A short air-gap, other things being equal, results in a large synchronous impedance, a large per cent. armature reaction ($q_A = A \div R$), a soft electromagnetic coupling, and a longer natural hunting period. This is desirable up to a certain point, as it decreases the frequency of hunting, improves the self-starting quality, increases the effectiveness of the damping devices and cheapens the machine; but there is an obvious limit to the desirable softness of coupling, namely, that beyond which there is danger of a motor breakdown. The value of $q' (= A'/F)$ should rarely be more than 0.6 when F is taken at full-load and unity power-factor. Also, referring to the Blondel e.m.f. diagram, it appears that with a large x_s (short air-gap) there will be a large variation in the power-factor of the motor from no-load to full-load under constant excitation, or a frequent adjustment of excitation will be demanded in order to maintain a constant power-factor.

79. Self-starting synchronous motors. The a.c. starting of the polyphase synchronous motor is as follows: If the field circuit of such a motor be opened and the armature be supplied with polyphase currents, there will result a fairly uniform field revolving around the periphery of the armature. Any energy transmitted across the gap to the field poles through the medium of this revolving field must be accompanied by a corresponding torque. Thus any hysteresis or eddy-current losses in the pole faces, due to the revolving field, represent a torque; or if the pole faces carry damping coils these will act as the short-circuited secondary of an induction motor, yielding a torque depending upon their reactance and resistance.

In this way a polyphase synchronous motor will supply a small starting torque, sufficient to start without load and run nearly up to synchronism; if it is a salient-pole machine it will then fall into step. Following this the field circuit of the motor may be closed and the motor is ready for the application of its load. If it is a non-salient pole machine, it will not come quite into synchronism until the field is excited, after which it will usually pull itself in step. It is sometimes even possible, with a little coaxing to start a polyphase motor when the only torque is that supplied by the hysteresis and eddy-current losses in laminated pole faces, although this is not a very satisfactory arrangement where frequent starting is required. With damping coils, however, a polyphase synchronous motor will start readily on reduced voltage and without excessive current.

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80. Polarity. During acceleration with open-field circuit, the induced polarity in any given pole alternates less and less rapidly as the speed approaches synchronism. The final polarity of any pole, when the speed has reached synchronism, is largely a matter of chance and obviously may not be the same as produced by the field current as connected. If these polarities are in opposition, the revolving part will slip back one pole when the field circuit is closed, the large time constant of the field circuit allowing this to take place without serious shock. It is safer, however, to determine the polarity before closing the field circuit, and reverse the latter if necessary.

81. Starting current. As the chief function of the starting current is excitation, the shorter the gap the less the current required.

The minimum starting current for polyphase synchronous motors is usually such as to require only a portion of the line voltage for starting purposes, this being obtained by means of induction starters. If, for example, a certain motor requires in starting, double full-load current at half line voltage, the line current at starting would be practically equal to the full-load running current.

82. Starting synchronous motors by external means. Where the starting current is objectionable to the system, external means, such as d.c. or induction motors, must be employed. With single-phase synchronous motors, this is obviously necessary.

Chapter VI, of "Design of Polyphase Generators and Motors," by Hobart, sets forth reasons for employing synchronous motors more frequently. This reference contains descriptions of methods of building synchronous motors with high starting torques.

83. Effect of differing impressed and induced wave shapes on power-factor. When the impressed and induced e.m.f. waves are of different shape, the unbalanced e.m.f. harmonics produce wattless harmonic currents, which though small compared to the full-load current may be considerable with respect to the no-load fundamental current. *Thus the p.f. at no-load may be less than unity even with the fundamentals of the current and e.m.f. in phase.*

METHODS OF SYNCHRONIZING

84. Necessary conditions. Impressed and induced e.m.fs. equal, opposite, and of same frequency.

85. Synchronising with lamps. Connect lamps in series between the in-coming machine and the line. When the lamps are bright (or dark, according to whether the machines are connected in unison or in opposition in the synchronizing circuit), and the beats are very slow, showing opposition of phase and approximate synchronism, the line switch may be closed and the machine will quickly settle down to stable operating conditions. If a motor, the load may then be applied.

In the case of a three-phase machine, lamps should be connected in at least two phases, and if both sets are not dark at the same time, there is indication that the three phases are not connected in the proper order and that two of them should be interchanged. The chief objection to the use of lamps for synchronizing is that they do not tell just when the two e.m.fs. are in exact opposition, nor whether the in-coming machine is fast or slow, although with a little experience it is possible to become quite proficient in their use.

86. Synchroscope. Various electromagnetic instruments called synchronizers, synchronoscopes, synchroscopes, etc., have also been devised for indicating synchronism. In most of these, the principle of operation is that of the rotary field, synchronism being indicated by a pointer on a dial. When the in-coming machine is above or below synchronism, the pointer revolves in one direction or the other respectively, and at a rate proportional to the slip (or beat) frequency. At synchronism the pointer stands still, and in a position on the dial which indicates the relative phase of the two e.m.fs.

One form of synchronizer is constructed as follows: The armature consists of two coils at right angles connected in parallel, a non-inductive resistance in series with one and an inductive resistance in series with the other. The stationary field coil is connected to the supply bus and the armature to the in-coming machine. The split-phase revolving field produced by the armature currents, reacts on the alternating field to produce a rotation whose speed is equal to the difference between the frequencies of armature and field currents. When these are equal the armature coil remains stationary.

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PARALLEL OPERATION OF ALTERNATORS

87. Mechanical analog. When two or more alternators are connected in parallel and driven at the same frequency, they are as if coupled together by an elastic coupling just as in the case of a synchronous motor connected to a generator. Thus they must run at exactly the same frequency as long as they are coupled.

88. Division of load. Consider two similar alternators driven by separate prime movers, of which the speed characteristics are shown in Fig. 62, as *a* and *b*. Then if the speed is that represented by the horizontal line *ss*, the powers supplied by the two prime movers will be P_a and P_b respectively. The division of load will then be wholly dependent upon the speed characteristics of the prime movers, *i.e.*, upon the governors.

89. Division of reactive current. The only effect of changing the excitation on either machine is to change the division of reactive current: *e.g.*, starting with equal loads and currents, if the excitation of *a* be increased, it will take more of the lagging reactive current, and *b* will take less. Any inequality of excitation is equalized by a circulating reactive current which transfers the excitation from the overexcited machine to the underexcited one. The terminal voltage will be determined in any case by the total excitation of both machines and by the magnitude and p.f. of the load.

When the voltage of a power plant is controlled by a Tirrill regulator, acting on the exciter bus from which the fields of all the parallel connected units are supplied, the per cent. increase in excitation for a given increase of load will obviously be the same on all the alternators. But if one alternator has a close regulation and another poor regulation, and if in the first case they shared the active and reactive currents in proper proportion, with increased load the close regulation machine will be relatively overexcited and will take more than its share of the lagging reactive current.

90. Switchboard control of speed of prime movers. In prime movers with very close speed regulation (no-load to full-load), it is obviously necessary that the two speeds be very closely adjusted (Fig. 62), and this is often difficult by the cut-and-try method, which in some cases requires shutting down each time to adjust the governors. Large units are often provided with a means of governor adjustment during operation. This may be accomplished by means of a small motor connected through worm gearing to the governor adjustment and controlled from the switchboard.

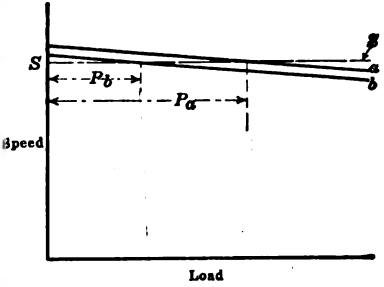


FIG. 62.—Diagram of division of load between two parallel-connected alternators.

91. Governor damping to prevent hunting. Sudden changes of load frequently cause the governor to hunt, *i.e.*, open up too wide, then close too far and so on. This may be easily prevented by a dash-pot connected to the governor.

ELEMENTARY OUTLINE OF THE DESIGN OF SYNCHRONOUS MACHINES

92. Specifications. Every electrical machine is built to meet certain specifications whether proposed by the purchaser, his engineer, or the manufacturer. In addition to the customary specifications there is always the question of first cost which must be reduced to a minimum. Many of these specifications, requirements, or standards are thoroughly treated in the Standardization Rules of the American Institute of Electrical Engineers; these are given in Sec. 24. For a synchronous alternator the specifications refer briefly to the following: frequency; number of phases; rev. per min.; terminal voltage; rated output in kv-a.; minimum power-factor;

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temperature rise (Sec. 24); efficiency (Sec 24); inherent regulation; per cent. leakage reactance volts; insulation tests (Sec. 24); wave form. These are not all specified in each case, whereas in some cases much more elaborate specifications dealing with the details of mechanical and electrical design are supplied. With reliable manufacturers, very simple specifications are ordinarily sufficient, telling chiefly what the machine shall accomplish rather than how it shall be built. In the case of many modern alternators, regulation is not a controlling specification, it being in most cases important to have a high reactance rather than a low one (Par. 63 and 64). Efficiency as such is also not directly a controlling factor in design, but chiefly as it is necessary to keep down the heat developed in the machine. A fraction of 1 per cent. in efficiency is not as important to the user as a safe operating temperature.

93. List of symbols used.

$\mathfrak{B}_1$ = Max. value of equivalent fundamental sine-wave of air-gap flux density (lines per sq. in.).
$\mathfrak{B}_g$ = Actual max. flux density in air-gap at pole-face (lines per sq. in.).
$\mathfrak{B}_{tr}$ = Maximum apparent tooth-density of flux (lines per sq. in.) in teeth.
D = Diameter at air-gap (inches).
d_s = Depth of slot (inches).
c'' = Volts induced per in. of active armature conductor.
f = Frequency (cycles per sec.).
k_c = Allowable copper watts per sq. in. of armature surface.
K = k.v.a. output.
K_a = k.v.a. developed in the armature.
k_b = Belt differential factor.
k_o = specific output.
k_p = pitch differential factor.
k_t = ratio of pole pitch to gross armature core length.
l = gross armature core length.
m = cir. mils per amp.
p = no. of pairs of poles.
q_A = ratio armature to gap amp-turns at full load.
q_{il} = ratio of net iron length of armature to gross length.
q_p = ratio of coil pitch to full pitch.
q_w = ratio of slot width to tooth pitch.
R = rev. per min.
T_a = Temp. difference in deg. cent. between armature conductor at centre and at end.
v = peripheral velocity, ft. per sec.
w'_c = wt. of armature copper (lb.) per kv-a. output.
Δ = peripheral loading; ampere conductors per in. of armature periphery.
ξ = output coefficient.
τ = pole pitch (in.).

94. Output equation. The volt-amperes per sq. in. of peripheral surface (Par. 24) are $\Delta e'' = 8.50 k_b k_p \Delta v B_1 10^{-8}$, and the total power developed, in kv-a. is, $K_a = 8.50 \pi k_b k_p \Delta v B_1 D l 10^{-11}$. Allowing a maximum drop of 5 per cent. between induced and terminal volts, and taking B_1 corresponding to full-load, the kv-a. output is

$$K = 2.54 k_b k_p \Delta v B_1 D l 10^{-10} = k_o D l \qquad \text{(kv-a.)} \qquad (28)$$

or since $D = 720 v \div (\pi R)$

$$l = 1.72 \times 10^7 K R \div (k_b k_p \Delta B_1 v^2) \qquad \text{(inches)} \qquad (29)$$

$k_o = 2.54 k_b k_p \Delta v B_1 10^{-10}$ is the **specific output**, or the kv-a. per sq. in. of projected area of the air-gap cylinder. By substituting for v its value $\pi DR/720$, we obtain

$$K = 1.11 k_b k_p \Delta B_1 D^2 l R 10^{-12} = \xi D^2 l R \qquad \text{(kv-a.)} \qquad (30)$$

where $\xi = K/(D^2 l R) = 1.11 k_b k_p \Delta B_1 10^{-12}$ is called the **output coefficient**. Taking $k_b = 0.950$ and $k_p = 0.95$, this may be written, $\xi = (\Delta/1{,}000)(B_1/10^4) 10^{-5}$. Sometimes k_o and sometimes ξ is more convenient as a starting-point for preliminary design, both being rough measures of the economy of material.

Major design constants. B_1, v and Δ are the major design constants, since their choice (R being specified) determines the general dimensions D and l of the machine. The larger these constants, the smaller in general will be the product Dl, and, within certain limits, the weight and cost of the machine. The considerations which govern the choice of these constants

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are so numerous that they cannot all be given their due weight in any direct method of attack. Some of the more important considerations and limitations are as follows: Par. **95** to **107**.

Ratio of pole pitch to core length.

$$k_3 = \tau/l = 3.5k_3k_p\Delta B_{tr}v^2 + (10^7fKR)$$

Number of poles.

$$2p = 120/fR \qquad (31)$$

Pole pitch.

$$\tau = 6v/f \qquad \text{(inches)} \qquad (32)$$

95. Tooth-density limit. In order to avoid excessive eddy-current losses in the slot conductors and in the teeth, the flux density B_{tr} at the narrowest part of the teeth should not exceed (for open slots) the values of Par. **42**, although for partly closed slots and stranded conductors 10 to 15 per cent. higher values are safe. B_g is related to B_{tr} as follows for the rotor or internal element, and parallel-sided slots:

$$\mathfrak{B}_g = \mathfrak{B}_{tr}q_{ti}(1 - q_{sw} - 2d_s/D) \qquad (33)$$

and for the stator or external element

$$\mathfrak{B}_g = \mathfrak{B}_{tr}q_{ti}(1 - q_{sw}) \qquad (34)$$

$\mathfrak{B}_g$ is usually slightly less than $\mathfrak{B}_1$, (the crest of the fundamental sine-wave of flux, see Fig. 23, and Par. **32**). Also in extreme cases the tooth saturation flattens the flux distribution curve still more. For laminations 0.014 in. thick, q_{ti} varies from 0.7, in an exceptionally well ducted core, to 0.8, in a poorly ducted core, and 0.9 in a core without ducts. Thus if $\mathfrak{B}_{tr}$ is assumed at its reasonable upper limit, and q_{ti} is known, the relation of $\mathfrak{B}_g$ to q_{sw} is fixed.

96. Heating limit. At 60 deg. cent. the copper loss under 1 sq. in. of armature surface is $h_c = \Delta/m$, the resistance of one circ. mil. inch of copper at 60° cent. being just 1 ohm. h_c is obviously limited: (a) by the heat dissipating power (H_s) per sq. in. per deg. cent. of temperature rise, (b) by the allowable temperature rise, T, (c) by the relative amount of core loss, and (d) by the relative amount of coil-end surface. Assuming average values of (b), (c) and (d), H_s will vary with the nature of the ventilation, the peripheral velocity, and the amount of heat thrown off by the rotor. For open, salient-pole machines, a very rough preliminary guide is

$$h_c = \Delta/m = 0.4(1 + 0.016v) \quad \text{(watts per sq. in.)} \quad (34a)$$

For high-speed turbo-alternators h_c has little relation to v, owing to the widely differing methods of ventilation, and varies from 0.8 to 1.6.

97. Temperature gradient in slot conductors. Assume that all the heat developed in the active conductor is conducted longitudinally to the coil ends. This is approached in high voltage stators. Then the temperature difference between centre and end of conductor will be $T_c = (P \times 127^2)/m^2$, where l is the gross core length in inches. Or if T_c be limited, l will be limited, thus $l = (m\sqrt{T_c})/127$. Thus the larger the value of m, the longer may be the armature core without excessive temperature differences. The table in Par. **98** gives the temperature differences in deg. cent. for various values of l and m.

98. Temperature differences between centre and end of armature conductors

l, Armature length (in.)	Temp. difference T_c (deg. cent.)			
	600 circ. mils per amp.	800 circ. mils per amp.	1,000 circ. mils per amp.	1,200 circ. mils per amp.
0	0.0	0.0	0.0	0.0
10	4.48	2.52	1.61	1.12
20	8.98	5.05	3.23	2.25
30	40.3	22.65	14.5	10.1
40	71.7	40.3	25.8	17.9
50	112.0	63.0	40.4	28.1
60	162.0	91.0	58.1	40.4
70	220.0	124.0	79.1	55.0
80	286.0	161.0	103.0	71.5
90	364.0	205.0	131.0	91.0
100	448.0	252.0	161.0	112.0

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99. Weight of copper vs. Δ. With $h_c(=\Delta/m)$ limited, m must increase with Δ. Then the total weight of active copper (also of total copper if k_s be unchanged) will be proportional to Δ.

100. Depth of slot. On the same basis the slot depth will be proportional to Δ^2. Slot reactance does not limit Δ and slot depth, as is sometimes the case with induction motors (see Par. **251**).

101. Armature-reaction limit. If on the score of regulation, e.m.f. wave shape, or stability, it be desired to keep $q_A(=A\div R)$ within any given limit, it might become necessary to limit the ratio $\Delta/\mathfrak{B}$, see Eq. 22, Par. **60.**

102. Choice of $\mathfrak{B}$ and Δ. From the standpoint of the economy of material or of the maximum output coefficient, that value of q_w is the best which results in the maximum product $\mathfrak{B}_1\Delta$. But since, for a given depth of slot, Δ increases as $\mathfrak{B}_1$ decreases, the maximum product will occur where the net width of slot (excluding insulation) is approximately equal to the minimum tooth width, *i.e.*, when $q_w > 0.5$. A considerable change in q_w from the exact value which makes $\mathfrak{B}_1\Delta$ a maximum, does not seriously reduce this product, so that considerable variations from the best value of q_w will be found, as there are other considerations involved.

$\mathfrak{B}$. Assume q_w chosen, *e.g.*, to keep down the ratio $\Delta/\mathfrak{B}$ (Par. **101**), or to make $\mathfrak{B}_1\Delta$ a maximum (Par. **102**). Assume also $\mathfrak{B}_{tr}$ as chosen (Par. **95**); then $\mathfrak{B}_t$ is given by Eq. 34.

Δ. Assuming h_c constant, the upper limit of Δ is likely to be set for turbo-alternators by the limited space for copper on the rotor, since this limits F, and A (and therefore Δ) must be smaller than F. A glance at Fig. 63 shows that the cost of copper is not likely to set the Δ limit. In fact, an

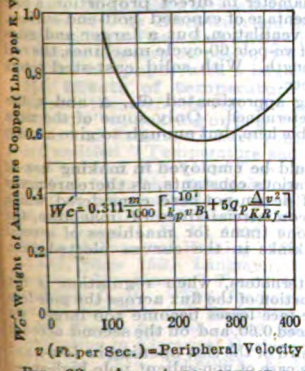


FIG. 63.—Armature copper per kv-a. vs. v, for a 10,000-kv-a. 25-cycle 2-pole turbo-alternator.

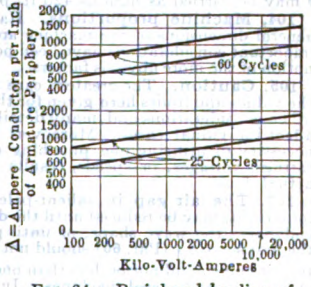


FIG. 64.—Peripheral loading of alternators.

increase of Δ, within certain limits, results in a more than balancing saving in iron. Moreover, the correspondingly larger m reduces T_c, the temperature difference between the centre and ends of the active conductors (see Par. **98**). If close regulation is specified, it may be necessary to use a low Δ and high $\mathfrak{B}_1$, see Par. **60**, particularly in high-speed turbo-alternators; but if, as is usually the case in modern practice, close regulation is not specified, Δ may be carried much higher than has heretofore been customary.

The following formulæ give a rough idea of the range of Δ for modern alternators: at 60 cycles $\Delta = (450 \text{ to } 700)\,(\text{kv-a.}/100)^{0.125}$; at 25 cycles $\Delta = (500 \text{ to } 800)\,(\text{kv-a.}/100)^{0.125}$. The higher values are for very well-ventilated and the lower for moderately ventilated machines (see Fig. 64).

103. Choice of peripheral velocity. Assuming that $\mathfrak{B}_1$ and Δ have been chosen, the choice of v determines the proportions of the machine. Coil-end reactance does not enter seriously into consideration, as in the case of the induction motor. The weight of active iron is nearly independent of v.

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The weight of armature copper is a consideration but a relatively unim portant one in high speed machines; in lbs. per kv-a. it may be expresse approximately as follows:

$$W'_a = 0.311\frac{m}{1{,}000}\left(\frac{10^7}{k_p v \mathfrak{B}_1} + \frac{1.5\times 10^7 q_p k_2}{k_p v \mathfrak{B}_1}\right)$$

$$= 0.311\,\frac{m}{1{,}000}\left(\frac{10^7}{k_p v \mathfrak{B}_1} + 5\,q_p\,\frac{\Delta v^2}{KRf}\right) \quad \text{(lb. per kv-a.)} \quad (3$$

which has its lowest value with respect to v when

$$v = 100\,\sqrt[3]{\frac{KRf}{k_p q_p \Delta \mathfrak{B}_1}} \quad \text{and} \quad k_2 = \frac{1}{3q_p} \quad (3$$

But for high speeds, this would result in a very long machine of sma diameter and hard to ventilate; so that larger values of k_2 are usually em ployed for high speeds.

In Fig. 63, W'_a is plotted against v for a case where the following valu obtain: $K = 10{,}000$; $f = 25$; $R = 1{,}500$; $\Delta = 1{,}200$; $\mathfrak{B}_1 = 40{,}000$; $q_p = 0.667$; k_p 0.866; $m = 1{,}000$; from which it is obvious that k_2 may be increased co siderably above the value corresponding to minimum copper, without co siderable increase of cost. As k_2 varies proportionately with v^2, it is critical ratio and useful as a guide to the determination of v, up to t mechanical limit. Rarely does k_2 occur outside of the range 0.6 to 1.4, beir in general larger as the number of poles decreases, although each case mu be considered by itself, and many other factors taken into account.

The *major considerations* affecting v are those of ventilation and mechanical design. A high v means a diameter in direct proportion, a co length inversely as v^2, a much larger percentage of exposed coil-end surfac higher heat dissipating power and better ventilation, but a larger and mo expensive frame and bearings. In large two-pole 60-cycle machines, the re upper limit of v is that of mechanical strength. With solid cast-steel roto v may be carried as high as 420 ft. per sec.

104. Machine proportions. Having approximated $\mathfrak{B}_1$, Δ and v, t general dimensions of the machine are determined. Only some of the mo important considerations have been possible here, but enough to give a cru notion of the more obvious factors.

105. Caution. The greatest care should be employed in making use the values and limits here given for the various constants, as there are ma other considerations and many details of design not here considered, whi affect individual cases. Moreover, in commercial lines of machines, t necessity of utilizing one punching or one frame for machines of sever ratings, voltages, or speeds, results in kinks in the curves plotted fro actual data.

106. The air gap in salient-pole alternators, when regulation is n important, may be reduced until the distortion of the flux across the pole fa endangers the wave shape, or until pole-face losses become too large. the first score q_A (Par. 60) should not exceed 0.60, and on the second accou the air gap should not be less than one-third of the slot opening in low-, a one-half in high-speed machines. In the case of non-salient pole high-spe turbo-alternators, one of the chief considerations governing the length of gap is that of providing a sufficient path for the ventilating air (Par. 12

107. Effect of number of slots. A small number of large slots mea more heating of armature conductors, poorer wave shape, less insulati and lower cost.

INSULATION

108. Stator-slot insulation. In the design of armature-slot insulati for high-voltage turbo-alternators, restrictions of a very serious nature encountered. It is a comparatively simple matter to insulate 600- windings and provide liberal factors of safety, but when dealing with windi for 12,000 volts, it becomes necessary to employ very high-grade mate and to observe many important precautions in the manner in which t materials are applied. For a given material the disruptive strength per of thickness grows less as the thickness is increased. In this circumsta lies a serious handicap in designing the insulation for rotating appar wound for high pressure. For stationary apparatus which can be immer in a tank of oil, reliance can be placed on the disruptive strength of the oil

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d interposed barriers of insulating material, but in the insulation of armature windings, great regard must be paid to economy in space, and, furthermore, we cannot have recourse to immersion in oil.

On alternating-current machines of 1,000 volts and upward, the armature-slot insulating material may consist of micanite, micarta or treated paper tubes, or of insulations built up of empire cloth, oiled linen, or other suitable materials. In Fig. 65 is given a curve showing suitable thicknesses of slot insulation from copper to iron in terms of the voltage.

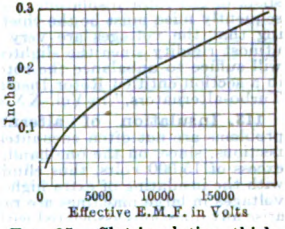


FIG. 65.—Slot insulation thicknesses for alternators.

109. For heat-resisting qualities and allowable working temperatures of different classes of insulations, see Sec. 24. Other references are as follows: A. P. Fleming and R. Johnson: "Chemical Action in the Windings of High-voltage Machines." *Journ.* I. E. E., Vol. XLVII, p. 530, 1911.

110. Instance and cause of an insulation failure. In 1905 Mr. J. S. Highfield published in *The Electrician* (Vol. LIV, p. 573) a description of an insulation failure in the windings of a 10,000-volt alternator. The failure was attributed to chemical actions stimulated by the ozone formed as a consequence of corona discharges. Highfield's article led to considerable correspondence in subsequent numbers of *The Electrician* and the views put forward are of great interest. "High-voltage Tests and Energy Losses in Insulating Materials," by Mr. E. H. Rayner appears on page 3, Vol. XLIX of *Journ.* I. E. E. (1912). Rayner concludes his paper with a large and valuable Bibliography of the subject.

111. Effects of temperature on disruptive strength. Lamme has dealt with these effects very thoroughly in his paper on "High-speed Turbo-alternators" appearing on page 1 of Vol. XXXII of *Trans.* A. I. E. E. (1913) Lamme and Steinmetz have continued the discussion of the subject in a paper entitled "Temperature and Electrical Insulation" which appears on page 79 of Vol. XXXII of *Trans.* A. I. E. E. (1913). As to the design of the insulation from the standpoint of the heat flow through it, the best information as yet available on the subject is contained in the following papers: Symons, H. D. and Walker, M. "The Heat Paths in Electrical Machinery," *Journ.* I. E. E., 1912, Vol. XLVIII, page 674. Williamson, R. B. "Notes on Internal Heating of Stator Coils," *Trans.* A. I. E. E., 1913, Vol. XXXII, page 153. Langmuir, Irving. "Laws of Heat Transmission in Electrical Machinery," *Trans.* A. I. E. E., 1913, Vol. XXXII, page 301. Randolph, C. P. "The Conduction of Heat; with Results of an Investigation of the Thermal Resistivity of Heat-insulating Materials," *General Electric Review* for Feb., 1913, page 120. Lamme, B. G. "Temperature Distribution in Electrical Machinery," *Trans.* A. I. E. E. (1916) Vol. XXXV, Part 2, p. 1471. Newbury, F. D. "Rational Temperature Guarantees for Large A. C. Generators," *Trans.* A. I. E. E. (1916) Vol. XXXV, Part 2, p. 1489. Kelly, R. "Internal Temperatures of A. C. Generators," *Trans.* A. I. E. E. (1917) Vol. XXXVI, p. 79.

112. Field insulation. For the field windings of low-speed and moderate-speed synchronous machines the problems associated with the insulation are comparatively simple. Wherever reasonably practicable, the field winding will consist of a flat-strip conductor wound on its thin edge. It is important that the design shall comprise features ensuring absolute absence of any relative motion between the conductors, as the result of centrifugal forces and of vibration. The use of coils of flat strip with the edges left bare in the customary manner, is excellent from the standpoint of ability to rapidly dissipate heat to the surrounding air in virtue of the rapid motion of these coils through the air. Since the voltage is low and the temperature moderate, it is practicable to employ the simplest methods, so far as the insulation is concerned. But in the case of extra high-speed turbine generators the field windings must be embedded in slots in the surface of the cylindrical rotor, and the difficulties to be overcome in providing a suitable design of insulation are very great. It is true that the voltage of the ex-

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citation is low, but the difficulty arises from the high temperature to whic the insulation is subjected and the high centrifugal forces to which th conductors are subjected. The facilities for ventilation are necessaril exceedingly poor, and the space for the copper is so restricted that it i necessary to operate the field winding at high current densities. Th result is that portions of the insulation in the slots of high-speed rotors ar usually subjected to temperatures much above 100 deg. cent. and frequentl temperatures approaching 150 deg. cent. are experienced at the very hottes spots of the rotor insulation in designs of the most difficult ratings. Con sequently mica must be the chief ingredient of the insulation, notwithstand ing that the voltages are very low. The construction must present th utmost rigidity since the slightest displacement of any insulating materia will suffice to unbalance the rotor. The case is ably presented by Lamm in a section entitled Rotor Insulation on p. 29 of his paper on "High-spee Turbo-alternators," in Vol. XXXII (1913) of the *Trans.* A. I. E. E.

113. Insulation of alternator leads and connections. Acut problems are not often encountered in the insulation of the leads and con nections, since, on the one hand, machines are rarely built for pressures i excess of 15,000 volts, thus eliminating the questions arising in connectio with the insulating of extra high-pressure leads; and, on the other hand, th voltages in large machines are rarely lower than 4,000, so that there do no arise any questions associated with the handling of very large currents. Thi latter statement should be conditioned by calling attention to the instan taneous current flowing on the occasion of sudden short-circuits. Such a current (Par. 63) may for an instant amount to from ten to twenty times th full-load current of the machine and is associated with the development o enormous mechanical forces. Consequently the problems of leads and con nections reduce chiefly to the provision of elaborate mechanical support fo all leads, conductors and cables from the armature windings to the switch board. The end connections of the stator windings must be elaborately supported; many fine machines were wrecked before this was realised. The end connections are sometimes lashed by stout bands of cord to heavy rings which are supported by stepped brackets constituting extensions of the frame of the machine. Also see the following:

Walker, Miles. "Short-circuiting of Large Electric Generators," *Journ.* I. E. E., 1910, Vol. XLV, p. 295.

Field, A. B. "Operating Characteristics of Large Turbo-generators." *Trans.* A. I. E. E., 1912, Vol. XXXI, p. 1645.

Lamme, B. G. "High-speed Turbo-alternators," *Trans.* A. I. E. E., Vol. XXXII, p. 1.

Davis, C. M. "Alternator Short-circuits," *Gen. Elec. Rev.*, 1914, p. 805.

Diamant, N. S. "Sudden Short-circuit Phenomena of Alternators," *Trans.* A. I. E. E. (1915), Vol. XXXIV, p. 2043.

114. Requisite protection against potential stresses caused by special conditions, grounded phase, switching, etc. If a Y-connected generator is operated with the common connection grounded without any resistance, then if a dead short-circuit to ground occurs on one of the three lines, although the circuit-breakers will at once disclose the faulty line, severe mechanical stresses will be imposed on the windings of the generator, due to the sudden short-circuit. If on the other hand, the neutral point is connected to ground through a resistance, the amount of current which can flow when a dead ground occurs on one of the lines will be limited by the amount of the resistance. Let us consider the case of a Y-connected generator with a pressure of 7,000 volts in each leg of the Y, and with a 9-ohm resistance to ground. If a dead ground occurs on one of the lines leading from the gen erator, then asuming that the resistance of the winding and line and ground aggregate 1 ohm, only $7,000/(9+1) = 700$ amp. can flow through th ground. But this will raise the potential of the neutral point from zero t $700 \times 9 = 6,300$ volts, and this combined with the pressure of the other tw phases, on which no ground has occurred, will increase the pressure betwe the high-tension ends of these windings and the frame of the machine about 12,000 volts. Thus while the use of a resistance between neutral a ground *decreases* the severity of the mechanical stresses to which the windin of the generator will be exposed on the occasion of sudden short-circu on the line, it *increases* the severity of the potential stresses on the ma insulation.

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The extra stresses imposed upon the main insulation of the machine would be still greater were the machine to be operated with its neutral grounded through a resistance, and with its terminals tapped into auto-transformers by means of which the generator voltage is stepped up (say in the ratio of 1:2) to the line pressure. Consequently when auto-transformers are employed, the generator must not have its neutral connected to ground through a resistance, but must be dead-ground. If the stepping-up is accomplished by means of transformers with distinct primaries and secondaries instead of with auto-transformers, then the generator's neutral may be grounded through a resistance. **Operation with grounded neutral** is to be preferred for systems from which many expensive underground cables are supplied, since a ground on some one cable will clear that cable off the line by the opening of its local circuit-breakers and without interruption to the rest of the system. But for a system consisting of a single long line with an important distribution system at its distant end, and where, consequently, any interruption of the supply would be very serious, there is a widely held opinion that the generator should be operated with non-grounded neutral, since it is maintained that the development of a ground at some one point of the line is then less likely to shut down the system. It will, however, increase, by 73 per cent., the extreme potential stresses across the generator's main insulation, and this must be recognized in the proportioning of the generator's insulation.

Switching operations, arcing grounds, lightning-arrester discharges, and other disturbances are likely to occasion surges in a system. The generator windings must be protected against the resulting high-potential stresses. Sometimes such protection is afforded by suitable reactances interposed between the line and the generator, and sometimes the last few turns in the winding are especially insulated so that the steep potential wave front shall not occasion breakdown between adjacent turns. See also page 164 of Vol. 53 (1915) of *Jour.* Inst. Elec. Engrs. for a description of the protection of an alternator by the "Circulating-current System." This is in a paper by E. B. Wedmore entitled "Automatic Protective Switch Gear for Alternating Current Systems."

LOSSES AND EFFICIENCY

115. Core losses. The data in the following table serves as an approximate guide to the determination of the *no-load* core loss in synchronous machines.

There are further core losses called *stray* core losses which increase as the load increases. These are due to the flux distortion in core and teeth, caused by the armature m.m.f.

Density in stator core (below slots) lines per sq. in.	Core loss in stator core (including teeth) (watts per lb.)	
	25 Cycles	60 Cycles
40,000	1.1	2.7
50,000	1.4	3.7
60,000	1.7	4.9
70,000	2.0	.....
80,000	2.4	.....
90,000	2.8	.....

116. Effect of rated speed on losses. Returning to a consideration of the no-load core losses it is of interest to note that the inherent nature of low-speed and high-speed designs is such that while the no-load core loss may constitute a relatively small component of the total loss in low-speed synchronous machines, it is necessarily a large component in high-speed synchronous machines. The reverse is the case with the armature copper loss, which is relatively high in low-speed machines, and relatively low in high-speed machines. In a group of 3,000-kv-a. 25-cycle close-regulation designs for various speeds, particulars of which are given by Hobart and Ellis in "High-speed Dynamo Electric Machinery" (John

Rated speed	No. of poles	*A* No-load core loss (%)	*B* Armature copper loss at full-load (%)	Ratio of *A* to *B*
83	36	1.93	.93	2.07
125	24	2.02	.73	2.77
250	12	2.17	.57	3.82
375	8	2.24	.50	4.45
500	6	2.27	.50	4.39
750	4	2.30	.47	4.92

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Wiley and Sons, N. Y., 1908), the rated speeds and these two losses in per cent. of output are given in the table at the bottom of the preceding page.

117. Armature copper losses. In addition to the normal I^2R loss, there are eddy current losses due to the flux fringing into the tops of the slots, depending largely upon the tooth density; and also eddy losses due to the cross slot leakage flux, depending largely upon the slot depth and the size of the conductor. Consequently each effective armature conductor is usually built up of many small component conductors in parallel. Since economy of space is of the utmost importance in the slots of extra high-speed alternators, each of these component conductors is usually of rectangular cross section. The subject of subdividing conductors to eliminate eddy losses has been dealt with by A. B. Field in a classical paper "Eddy Currents in Large Slot-wound Conductors," *Trans.* A. I. E. E., 1905, Vol. XXIV, p. 761. Also see "Eddy Currents in Stator Windings," a paper read by H. W. Taylor before the Inst. Elec. Engrs. in January, 1920, and abstracted in the London "Electrical Review" for January 23, 1920, at p. 102. Also see "Stromverdrängungsfreie Leiter für Wechselstrom," by L. Fleischmann at p. 203 of Archiv für Elektrotechnik, Vol. VIII (1919).

118. The field copper loss is usually of moderate amount in salient pole machines, even in cases where the machines have many poles. In non-salient pole machines this loss is, for designs of all speeds, a fairly considerable component of the total loss in a machine. For relatively low-speed machines this is partly due to the relatively large number of field spools among which the loss is distributed and each of which must provide a fairly large magneto-motive force. In extra high-speed machines, the considerable amount of field copper loss is, in part, a consequence of the high armature magneto-motive force per pole to be offset at low power-factors. In addition it can partly be traced to the deep air gap which must be provided in order that sufficient cooling air may be circulated through the machine. Finally, field copper loss in this type of machine is high, because of the limited space in the rotor slots, which renders it necessary to employ somewhat high current densities, in spite of the consequent high temperatures. Furthermore, in contrast to the salient pole machine, the field poles link with the flux at relatively low density, and some of them also link with only a part of the flux.

119. Actual windage and bearing-friction losses, for ten large turbo-alternators

No. of poles	Rated output (kv-a.)	Speed (rev. per min.)	Circulating air (cu. ft. per min.)	Losses in kilowatts				
				Friction of bearings for the set	Do. for the generator alone	Windage of gen. excl. of fan	Do. of fan	Friction and windage of generator
4	2,500	1,800	13,000	25	13	40	11	64
4	3,125	1,800	13,800	27	14	40	11	65
4	6,250	1,800	17,000	63	33	46	21	100
4	9,375	1,800	26,500	.....	.....	.....	.....	.....
4	12,500	1,800	27,000	.....	.....	.....	.....	.....
2	16,670	1,500	40,000	.....	80	80	80	240
2	5,600	1,500	18,000	.....	43	40	20	103
2	35,000	1,500	65,000	156	75	130	120	225
2	6,250	3,600	16,000	32	20	50	50	120
4	33,300	1,800	.....	138	75	220	230	525

120. Windage and bearing-friction losses. When the air circulation is provided by fans integral with the rotor of a turbo-generator, the windage loss may be taken at about 3 watts per cu. ft. of air circulated per min., depending upon the efficiency of the fan employed and with the design of the passages in the machine through which the air is circulated. The quantity of air required for cooling extra high-speed synchronous machines ranges from 2 to 5 cu. ft. per min. per kv-a. (Par. 132). In large steam turbine-driven alternators, the total windage loss is usually a matter of about 1.5 per cent

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of the output. Of this amount, about half represents the power required to drive the fan.

For moderate-speed and slow-speed machines not employing fans for ventilation, allowances ranging from 1.0 per cent. in small machines down to 0.5 per cent. in large machines are usually made for windage and bearing friction. A further consideration controlling the magnitude of the allowance relates to the number of bearings whose friction loss should fairly be charged to the generator as distinguished from the prime mover. Where, for testing purposes, the synchronous machine can be separated from the prime mover and driven by a small motor, the windage and bearing-friction loss may be determined by test when the machine is built.

121. Calculated values of bearing friction for several turbo-alternators

No. of poles	Rated output (kv-a).	Speed (rev. per min.)	Bearing friction in horse-power		
			Turbine bearing	Middle bearing	Bearing at collector end
4	9,400	1,800	7	62	24
4	6,300	1,800	11	60	14
4	6,300	1,800	6	41	13
4	3,100	1,800	4	25	5
4	2,500	1,800	6	21	6
2	2,500	1,500	3	20	4

At present the tendency is to reduce the length of the bearings and obtain lower losses.

122. Summary of losses. We have now reviewed the component losses in synchronous machines. These are: (a) no-load core loss; (b) extra core loss increasing with load; (c) full-load copper loss in armature winding; (d) eddy loss at full-load in armature winding; (e) field copper loss at full-load; (f) windage and bearing friction loss.

Losses (a), (c), (e) and (f) may be considered accurately determinable either by test or calculation. Losses (b) and (d) are not commercially determinable; *i.e.*, their determination would require an elaborate and expensive investigation in each case. A reasonable value may be assigned to the sum of losses (b) and (d) (Par. **127**), in cases where they cannot be determined from tests. It may in general be stated that all the losses except loss (b) and loss (d) are readily susceptible to either exact or sufficiently approximate determination, and hence they may be designated as **determinable losses.** It is in commercial transactions futile to attempt to conclusively determine losses (b) and (d). Consequently it is desirable to group these two losses together, and to designate them as: **indeterminable losses or stray losses.**

123. The efficiency.* The true efficiency of a machine is the ratio of the output to the input. The efficiency should be based upon the rated output, pressure, power-factor and speed. The losses on which the efficiency is based, should be corrected to 75 deg., the temperature of reference for efficiency determinations (see Sec. 24). The determination of the true efficiency of a machine involves either an accurate determination of all the component losses, or else an accurate measurement of the output and of the simultaneous input. In other than small machines, both of these methods of determination are impracticable unless resort is made to expensive scientific measurements.

Consequently in practice, use should be made of two approximate efficiencies. These may be designated as follows: (a) the efficiency exclusive of stray losses; (b) the conventional efficiency.

124. The efficiency exclusive of stray losses. This is the ratio of the output of the machine to the sum of the output and the determinable losses as obtained by the separate measurement or calculation of each determinable loss. This efficiency is necessarily greater than the true

* See also "The Determination of the Efficiency of the Turbo-alternator," by Barclay and Smith at p. 293 of Vol. 57 (1919) of the *Journ.* I. E. E.

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efficiency, but approaches it in machines in which the indeterminable losses are negligible.

125. The conventional efficiency differs from the efficiency exclusive of stray losses, to the extent to which appropriate values for the indeterminable losses are included in estimating the input. In all matters relating to guarantees, the allowances to be made for the indeterminable losses are specified in each case. The conventional efficiency is, by definition, less than the efficiency exclusive of stray losses, except in cases where the convention is to take the stray losses equal to zero (see Standardization Rules, Sec. 24). With the application of a reasonable amount of care in assigning appropriate values to the indeterminable losses, the difference between the conventional efficiency and the true efficiency should usually be quite unimportant and often negligible.

126. Stray losses. A realisation of the extensive nature of the stray losses has only gradually taken place. It is by no means unusual for the stray losses to amount to from 25 to 50 per cent. of the no-load core loss. These stray losses arise from various causes; a notable cause exists in the local variations in the reluctances of the magnetic circuits around the individual slots and groups of slots with the continually varying relative positions of stator and rotor. Although such losses are not a function of the no-load core loss, nevertheless practical purposes are sometimes fairly served by assuming the stray losses to be equal to half of the no-load core loss. For example, in a certain machine with a rated output of 2,000 kw. we may have the following losses: armature copper loss, 10,000 watts; field copper loss, 20,000 watts; core loss at no-load, 12,000 watts; bearing friction and windage, 15,000 watts.

With this assumption as to the stray loss, the total of all losses at full-load amounts to $10,000+20,000+12,000+15,000+6,000=63,000$ watts. The full-load efficiency will then be taken as: $2,000,000/(2,000,000+63,000)=96.9$ per cent.

127. Determination of stray losses. An approximation to the stray losses may be obtained by operating the machine at its normal speed and with sufficient excitation to circulate rated current. From the power required to operate the machine thus, the friction loss and the copper loss should be subtracted, and the remainder taken as the stray loss at full-load. Experience indicates that in many cases this is a fair approximation.

128. Variation of stray losses with load. The nature of the stray losses is too vague to justify any positive statement as to the laws of its variation with the load. It may in some instances vary as the square of the load. But with a view to practical liberality it is well to determine upon a representative figure for its full-load value and arrive at figures for its value at other loads by assuming it *directly* proportional to the load.

VENTILATION

129. The process of cooling and ventilating low-speed and medium-speed synchronous machines is not one presenting any grave difficulties, since such machines are so large as to expose extensive surfaces to the surrounding air. In such machines the field coils are usually arranged on the salient poles of the revolving field. The fan action occasioned by the revolution of such a salient-pole field, may be readily supplemented by the provision of fan blades suitably disposed on the rotating structure. The fan friction is one component of the losses in the machine, and serves to decrease the machine's efficiency, particularly at light loads. The power required to drive the fans of such machines is comparatively small since the pressure developed by the fans is low. See also "Ventilation as a Factor in the Economical Design of Electrical Machinery," by Edgar Knowlton at pp. 406 and 595 of Vol. XIX (1916) of the *General Electric Review*. Also "Ventilation Systems for Steam Turbine Alternators," by Edgar Knowlton and E. H. Freiburghouse at pp. 240 and 367 of Vol. XXI (1918) of the *General Electric Review*.

130. Stator ventilation. Owing to the rapid flow of heat by conduction from the copper in the slot to the end connections, it is not always necessary to provide vertical ventilating ducts in the laminated core of a narrow machine provided it is arranged to cool the end connections vigorously. When this principle is employed, it is practicable, in reasonably narrow machines, to maintain the armature windings at a low temperature without

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resorting to the relatively expensive method of providing vertical ventilating ducts. In many high-voltage machines the thickness of slot insulation is such that most of this heat must flow to the coil ends, even with comparatively long coils, Par. **97–98.**

131. **Rotor ventilation affecting diameter.** From the standpoint of rotor ventilation, a large diameter and a short core-length are desirable and permit of economy in field copper. But the gain, as regards decreased outlay for copper and magnetic iron when a large diameter is employed, may involve a very disproportionate increase in the outlay for frame and for bearing supports and for structural material in general.

With vertical-shaft machines it becomes practicable to resort to larger diameters than with horizontal-shaft machines, since in the latter type a short machine of large diameter requires a lavish outlay for material in order to render the stator frame sufficiently stiff to ensure absence of sagging. Any sagging would unbalance the air gap, which must be of uniform depth over the entire circumference.

The field winding should usually consist of flat copper, wound on its thin edge. The heat then readily flows to the outer surface, and is carried away by the surrounding air.

132. **Intense forced cooling and ventilation.** Extra high-speed steam turbine-driven generators of large capacity present the most extreme instances of the necessity for forced cooling and ventilation. The quantity

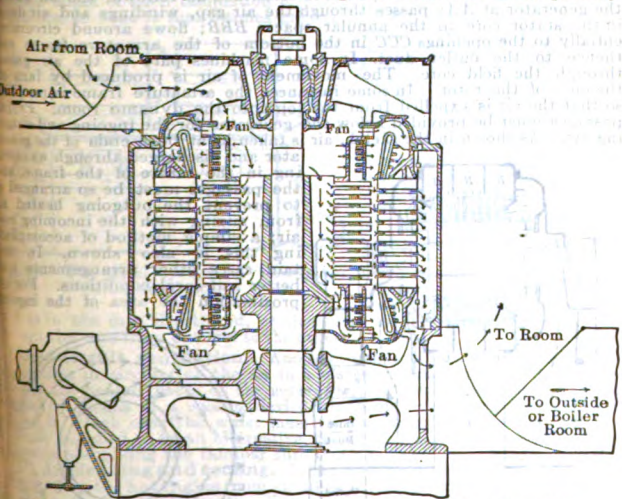


FIG. 66.—Ventilation design for a vertical-shaft turbo-alternator.

of air which must be forced through such machines per kv-a. of rated output in order to limit the temperature rise at full-load to permissible values, is of the order of from 2 cu. ft. per min. for a 50,000-kv-a. machine to 4.5 cu. ft. per min. for a 5,000-kv-a. machine, depending on the efficiency of the machine. The precise values vary with the arrangement of the ventilating passages, and the speed. The customary method of circulating the air consists in providing the rotor with fans which force air through appropriate passages. Fig. 66* relates to the ventilating method employed in the design

*From an article by E. Knowlton, "Ventilation of Steam Turbine-driven Alternators," *General Electric Review*, Oct., 1912, page 656.

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of a steam turbine-driven alternator of the vertical type. Mr. B. G. Lam has dealt very fully with this subject in a paper entitled "High-Spe Turbo-alternators," at p. 1 of Vol. XXXII (1913) of the *Trans.* A. I. E. Lamme subdivides methods of cooling turbo-alternators by the forced cir lation of air into three classes: (a) radial methods, (b) circumferent methods, and (c) axial methods.

133. In the radial system of ventilation all the air passes out radia through ventilating ducts in the stator core. In the design of these hi speed generators the rotor diameter is limited by the peripheral speed. C sequently the design is of relatively great length parallel to the shaft. Th is very little space on the rotor even for the windings, owing to the limi radial dimensions, and it is often necessary to dispense with the circulatio air through the interior of the rotor. Even in the most favorable cas such circulation of air through the rotor is limited to but a small part of air required for the cooling of the stator. The greater part of the sup required for the stator is, in the radial system, first passed along the gap; the radial depth of the air gap is often made very great expressly ou consideration for providing sufficient section for the flow of the requi amount of air.

134. A typical arrangement of the radial system as applied the General Electric Co. in its horizontal steam-turbine alternators shown in Fig. 67. The system is described as follows: the air ent the generator at *AA*; passes through the air gap, windings and air du in the stator core to the annular spaces *BBB*; flows around circumf entially to the openings *CCC* in the bottom of the armature frame thence to the outlet duct. In some machines part of the air pas through the field core. The movement of air is produced by fans the ends of the rotor. In some instances the armature frame is modif so that the air is expelled from the top into the dynamo room. Pro passages must be provided below the generator for the ingoing and out ing air. As shown in the sketch, air is taken in at both ends of the ge ator and discharged through an op ing in the centre of the frame, the passages must be so arranged to prevent the outgoing heated from mixing with the incoming air; a simple method of accompli ing this is also shown. In tain cases other arrangements better suit local conditions. For proximation the area of the ingo

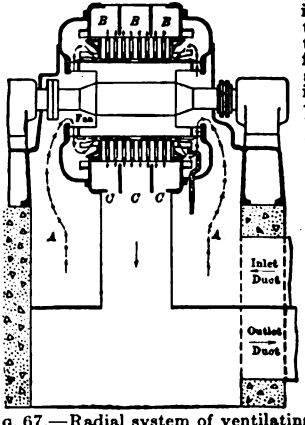


FIG. 67.—Radial system of ventilating a horizontal-shaft high-speed generator.

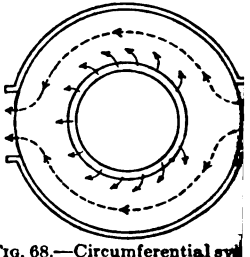


FIG. 68.—Circumferential sy of ventilating turbo-alterna

or outgoing duct will range from 5 sq. ft. for a 1,000-kv-a. to 60 for a 50,000-kv-a. generator. The outgoing air should be carried side the building, care being taken that it cannot immediately re the intake. The ducts should be as short and have as few bends as po and these should be made with a large radius. Both ducts should adjustable dampers so that part of the air may be taken from or ex

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into the engine room. This will allow adjustments to suit weather conditions. The armature and field leads are brought out from the bottom of the generator frame, directly under the collector; this brings them to the air chamber under the armature. From here to the switchboard the leads may be carried in one of the air ducts or a separate duct, as is most convenient.

135. **The circumferential system of ventilation** is explained by reference to Fig. 68 (Lamme). The air enters at one side of the machine and is forced along the air ducts in the stator core back of the armature windings until it reaches the other side of the machine, whence it is discharged. Such circumferential circulation is usually supplemented by the supply of a further amount of air to the air gap to cool the rotor, as shown by the 13 little arrows curved toward the centre of the diagram. This air, after leaving the air gap passes into the stator ventilating ducts and reinforces the main streams of air. Lamme also illustrates in his paper (Ref. in Par. 132) a modification of the circumferential system in which the air enters the stator ducts at points of their outer circumference, flows down alternate vertical ventilating ducts in the stator core, then a short distance through longitudinal ducts, and returns through the intermediate vertical ventilating ducts back to the outer circumference of the stator.

136. **The axial system of ventilation** (often termed the longitudinal system) is illustrated in Fig. 69 (Lamme). The system has the advantage that the edges of each lamination are bathed by the circulated air. The conduction of heat is many times greater in the plane of the laminations than transversely thereto, the ratio varying from 20 to 100 according to the nature of the insulation between laminations, the thickness of the laminations, insulation, and their compression. Obviously the longitudinal method has a decided advantage in this respect at least. On the other hand it is difficult to arrange that a sufficient extent of surface shall be exposed to the air. As shown in Fig. 69, there is provided in the axial system a large number of longitudinal passages. These passages may lead to a large central outlet duct as in the case illustrated, or they may extend uninterruptedly right through the core from one end to the other.

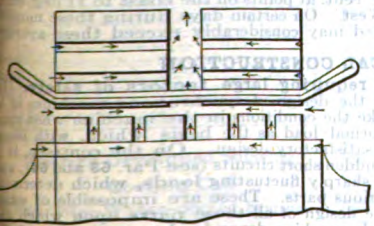


Fig. 69.—The axial system of ventilating turbo-alternators.

Closed-circuit ventilation. Another means of providing clean, cool air consists in circulating the air in a closed circuit. After each passage through the heated parts of the generator, the temperature of the air is reduced by means of a cooling device which may consist of the usual air washer, in which case the water must be discharged and new water continuously supplied. As an alternative, the cooling may be accomplished by apparatus resembling the familiar auto-truck radiator.

137. **Air cleaning and cooling.** It has been quite usual to take the ventilating air from the hot engine room, circulate it through the machine, and then return it to the hot engine room. Not only does this result in a high operating temperature (or else a lower output for a given temperature), but it also has the consequence that the air which is sent into the machine has taken up oily vapors whose presence aggravates the difficulties associated with the gradual clogging up of the ventilating passages in the machine with dust and dirt which is also carried into the machine in the circulating air. An expensive periodical cleaning of the machine must be undertaken.

In several important modern stations it is arranged that the air shall be taken from outside the station or from a cool basement (when one of sufficient capacity can be provided) cleaned by passage through cloth screens, and then led to the machine through suitable ducts. The cloth employed is of a closely woven variety similar to that known as Canton flannel, and there is required a surface of some two-tenths of a square foot per cu. ft.

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of air per min. These screens occupy a great deal of space, they gradua become clogged with dust, and constitute a fire risk.

138. Air washing. Decidedly the best method of cleaning the air consi in passing it through sprays of water to wash it, instead of straining through cloth screens. E. Knowlton and E. H. Freiburghouse deal length with this method in the course of an article entitled "Ventilati Systems for Steam Turbine Alternators," in the *General Electric Rev* for April and May, 1918. See also a paper by J. Christie, entitled " Filtration, Cooling and Ventilation of Electrical Machinery;" Electri Review; June 27, 1913, page 1088. Mr. Christie states that filter clo wear out quickly and are expensive to renew. He states that $400 to $ per annum for cloth and labor is by no means an outside figure for t efficient maintenance of this equipment.

139. The cooling of air incident to water filtering. The humi fication of air in its passage through the water filter occasions a lower of its temperature, the amount of which varies with the condition of the a If it is utterly dry on entering the humidifier, the air will have experienced considerable decrease in temperature by the time it has emerged from t humidifier and entered the machine which is to be cooled. As a consequence these considerations, it is obvious that the average conditions regardi humidity and temperature in any locality, affect the amount of advanta to be derived by air filtering in addition to that of removing the dirt a the dust. The average reduction in the temperature of the air for t months of July and August in different parts of the United States is stat (Knowlton) to vary from 2.5 deg. cent. at points on the coast to 11 deg. ce at points in the Middle South West. On certain days during these mont the maximum reduction effected may considerably exceed these avera values.

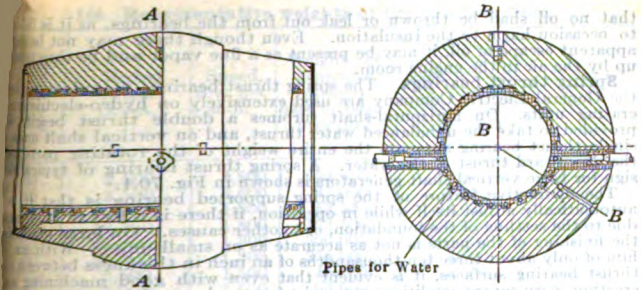
MECHANICAL CONSTRUCTION

140. Abnormal conditions requiring large factors of safety. providing adequate strength in the design of synchronous machines it usually utterly insufficient to take the conditions in the machine when r ning at uniform speed at its normal load as the basis which, with usu factors of safety, will lead to a satisfactory design. On the contrary, it the conditions occurring during sudden short circuits (see Par. **63** and **64**), a when the machine is carrying sharply fluctuating loads, which determi the strength required in the various parts. These are impossible of ex calculation; consequently, in the design of all those parts upon which t mechanical strength of the whole machine depends, large margins of t nature of safety factors must be added to the values which would usua be employed in machine design.

141. Critical speed of shafts. Irrespective of questions of cost, con tions arise with some capacities and speeds where it is impossible to fi room for a shaft of large diameter, and it must have a critical speed below t operating speed. The peripheral speed at the bearing would otherw exceed desirable values; furthermore, there is but limited room for acco modating the windings in the radial depth available between the surface the rotor (which is itself of small diameter) and the surface of the shaft.

142. Effect of critical speed on rotor design. If the critical speed to be well above the normal running speed, it is impracticable to emp laminated rotor bodies for capacities much above 1,000 kv-a. at a speed 3,600 rev. per min. or above 5,000 kv-a. at 1,800 rev. per min. or above 7,5 kv-a. at 1,500 rev. per min. But for designs in which the critical speed below the normal speed, it is practicable to employ rotor constructi with laminated cores up to ratings of 3,000 to 4,000 kv-a. at a speed of 3,(rev. per min. of some 10,000 to 15,000 kv-a. at a speed of 1,800 rev. per m and of some 20,000 kv-a. at a speed of 1,500 rev. per min. In the constr tion of 1,500 rev. per min., 25-cycle, or 3,600 rev. per min., 60-cycle rot solid cores are especially appropriate, since greater mechanical strength be obtained in constructions in which the slots for the windings are milled of a solid steel core. The rotor windings may be retained in the slots solid steel or brass wedges, since the magnetism is of constant direction each part and since the air gap is so deep in these extra high-speed generat that there is no loss in the rotor surface from pulsating influences fr the alternating m.m.fs. due to the conductors in the stator slots. In so designs the shaft ends consist of enlarged extensions bolted to the rotor c

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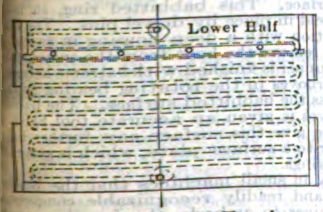


FIG. 70.—Water-cooled bearing.

Water is circulated through these tubes and plays a large part in maining the temperature of the bearing t a safe value.

The following description relates o the water-cooled bearings of some horizontal turbo-generators built by the General Electric Company.

The general construction, including the arrangement of the cooling pipe and the grooving, is shown in Fig. 70. The bearing is provided with a coil of thin copper tubing cast into the babbitt lining close to the surface and having at the ends of the tubing, steel blocks securely brazed to the tubing and held in place by the babbitt. Water is led into the bearing by pipes passing through stuffing boxes in the bearing standard. These pipes must be removed before taking out a bearing shell. In this way the heat of the bearing is taken up at the point where it is generated and there is no cooling oil needed in oil tank or in pipes.

In the case of vertical shaft machines the step bearing is maintained in condition by forced circulation of oil. It is important in the design of the bearings for electrical machinery

143. Bearing lubrication. In small and medium sized machines of moderate speed, the lubrication of the bearings is accomplished in the usual manner by oil rings located in suitable recesses in the bearing and with their lower portions immersed in oil below the bearing lining. In large extra high-speed machines, the oil is forced into the bearings and after passing from them and being allowed opportunity to cool, it is again forced into the bearings. Sometimes in such machines and frequently in large water-wheel generators, copper tubes are embedded in the bearing just under the surface of the lining metal.

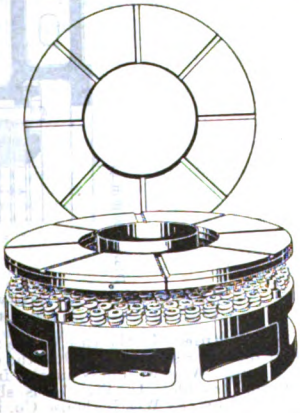


FIG. 70A.

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that no oil shall be thrown or leak out from the bearings, as it is li to occasion harm to the insulation. Even though there may not be apparent escape of oil, it may be present as a fine vapor and be thus ta up by the air in the engine room.

Spring thrust bearings. The spring thrust bearings manufactured the General Electric Company are used extensively on hydro-electric erating units. On horizontal-shaft turbines a double thrust bearin provided to take the unbalanced water thrust, and on vertical shaft uni single thrust bearing supports the entire weight of the rotating parts the downward thrust of the water. A spring thrust bearing of typical sign for large vertical shaft generators is shown in Fig. 70*A*.

The distinctive feature of the spring supported bearing is that it automatically adjust itself while in operation, if there is a loss of alignm due to the settling of the foundation, or to other causes. On large machi the finishing of the parts is not as accurate as on small units. With an film of only about three ten-thousandths of an inch in thickness between thrust bearing surfaces, it is evident that even with good machining erection, very severe conditions may exist for any large thrust bearing wi out a yielding support.

The bearing consists of a runner of a special grade of cast iron resting o thin steel disc with a babbitted surface. This babbitted ring, in tu rests on short helical springs and is held in place by dowel pins. The h base casting shown is used in connection with a deep housing in case i desired to instal water cooling coils to remove the heat from the surround oil bath. The bearing surface of the runner is finished with extreme accur and is given a high polish. Radial grooves in the rotating bearing surf produce a rapid circulation of oil across the babbitted surface. The babb surface upon which the runner revolves is given an accurate tool finish the factory, and it is not necessary to give this surface any further fin such as hand scraping to the runner or to a surface plate, which is gener done in the case of other types of bearings.

144. Bearing pedestal. It is only in small machines that the bear pedestal continues to be a distinct and readily recognizable compone There is a tendency in modern machines to embody the functions of t pedestal either in the base or in the end shields.

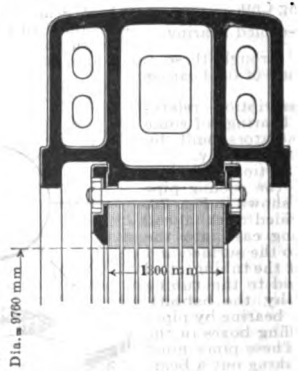


FIG. 71.—Box-type frame for 5,000-kw. alternator.

145. Frame. In the case of the frames of low-speed alternators of great diameter and small width, the design should be liberally stiffened deep ribs. Any weakness in the frame of such a machine is certa occasion trouble. In Fig. 71 is shown a liberal, box-type constru employed by the Westinghouse Co. in the design of a 5,000-kw. alterna The internal diameter of this armature is 9.76 meters.

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146. Representative weights of turbo-alternators

Frequency (cycles per sec.)	Rated output (kv-a.)	Speed, rev. per min.	Weight of generator without base or bearings (lb.)	Weight of turbine including base and bearings but exclusive of accessories (lb.)	Weight of set (lb.)
60	2,500	1,800	34,600	76,000	110,600
60	2,500	3,600	33,000	36,000	69,000
60	5,000	1,800	53,570	93,000	146,570
60	12,500	1,800	133,500	256,000	389,500
60	25,000	1,200	300,000	510,000	810,000
60	50,000	1,200	350,000	575,000	925,000*
25	2,500	1,500	49,000	73,600	122,600
25	5,000	1,500	96,900	120,500	216,400
25	12,500	1,500	180,300	277,000	457,300
25	25,000	1,500	340,000	452,000	792,000
25	39,000	1,500	305,000	395,000	700,000*

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THE TESTING OF ALTERNATING-CURRENT GENERATORS

148. The heating test of large alternators under normal full-load nditions is troublesome and expensive, even when the necessary amount power is available, and many suggestions, such as those of Mordey and of hrend,† have been made with a view to reduce the amount of energy sted during the tests. These methods necessitate alterations in the nnections of either the armature coils or the magnet coils. If serious chanical stresses are to be avoided, these methods can only be employed th machines having very large numbers of poles, and even then the magtic conditions are not accurately the same as those which exist at normal ll-load. The following method, known as the "intermittent short-circuit d open-circuit method," or, briefly, the "intermittent method;" involves change whatever in the connections of the machine, and requires the penditure of only sufficient energy to cover the losses of the machine, and t every part of the alternator reaches the same temperature as it would ter an actual full-load heating test. The method involves a previous owledge of the separate losses of the machine, but these are, in any case, termined in the ordinary course of a systematic test.

*All the values in the table except these two, represent practice prior to 915. The two added values represent very recent designs and afford a od illustration of the rapid progress in reducing the weight per kv-a. in rbo-alternators of very large capacities.

†These methods are described by Mordey, *Journ.* I. E. E., Vol. XXII, 93. Behrend, *Elec. World and Engineer*, Vol. XLII, Oct. 31 and Nov. , 1903.

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149. Intermittent method of making a heating test. Suppose certain machine has at full-load: a friction loss of 10 kw.; an armature copp loss of 20 kw.; and an iron loss of 100 kw. In the course of an hour's run full-load the loss of energy will be: $10 \times 60 = 600$ kw-min. as friction; $20 \times$ $= 1{,}200$ kw-min. as copper loss in armature; $100 \times 60 = 6{,}000$ kw-min. iron loss.

Let the machine run for 5 min. with the armature short-circuit and at such an armature current that the armature copper loss is 60 k *i.e.*, at a current equal to $\sqrt{3}$ times the normal current. Next let the mach run for a further 10 min. with open armature circuit, but overexcit so as to give an iron loss of 150 kw. This adjustment is made according i ndications of the wattmeter on the driving motor, allowance being made other losses, such as losses in the motor itself and friction of the alterna and the driving mechanism. If this cycle of operations is repeated regula throughout the time of the test, it is obvious that $10 \times 60 = 600$ kw-m will be lost in friction per hr.; $60 \times 20 = 1{,}200$ kw-min. will be lost in armat copper per hr.; $150 \times 40 = 6{,}000$ kw-min. will be lost in the iron per hr., exactly the same loss in each case as would have occurred under norr full-load in the same time. There is still the **loss in the magnet windir** to be considered. During the short-circuit test this is less, and during open-circuit test it is greater than the normal, so that on the average it d not differ very greatly from the normal. If, however, great exactness this respect is required it is obtained as shown in Par. **150.**

150. Further refinements of the intermittent method of maki a heating test. In the above example one-third of the time of each per of the test was devoted to the short-circuit test, and two-thirds to the op circuit test. These proportions may, however, be changed at will, and varying the short-circuit current and the overexcitation corresponding the total energy expended in the armature copper and iron per hr. may kept at the right value, while the average exciting energy will have so value other than before. Except in very extreme cases, *e.g.*, in the case alternators which require only a very small change in excitation betwe no-load and full-load, and which at the same time have a very low value the ratio of short-circuit current at full excitation to normal full-load curre it is always possible so to adjust the two time intervals, that wh keeping the copper loss and the iron loss per hr. at the correct val the exciting loss per hr. has practically the same value as at normal f load. Exactness is, however, unnecessary, as, in any case, a simple calcu tion will always enable the temperature rise of a field coil at the correct f load loss to be determined from the temperature rise measured at so slightly different known number of watts. See Hobart, H. M., "Electri Machinery Tests and Specifications Based on Modern Standards," *Tra* A. I. E. E., Vol. XXXV (1916), Part II, p. 1278.

151. Pre-heating, before a test, with excessive currents. A gr saving in the time required to test a large generator may be effected applying excessive losses for a sufficient time before the commencement the periodic test above described, and thus heating the machine up to maximum temperature it is likely to reach. The continuation of the int mittent test (Par. **149** and **150**) for a very few hours will then, even the case of the largest generators, allow the steady final temperature to reached.

152. The calculation of the copper losses requires measurements the resistance of the windings. When the windings are of sufficiently h resistance and low current capacity, the resistance is most readily determi from the pressure in volts required to maintain through the windin known current. When the winding is of very low resistance and of h current-carrying capacity, the best method generally consists in connect it in series with a conductor of a known resistance of the same order magnitude, and comparing by a millivoltmeter the pressure across each the resistances when carrying a considerable current. Obviously the va of the current need not be known.

153. The friction and windage losses and the iron losses should measured by driving the alternator by a motor of which the efficie is known for all values of the input. The motor should, if practica

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be directly coupled to the alternator. This will usually be impracticable, hence, in most cases an allowance must be made for the loss in the driving belt. The capacity of this motor should preferably not be much greater than sufficient to drive the alternator on open circuit with full excitation of its field circuit. The motor will thus always be operating either well on toward its full-load, or else at overloads, and its efficiency will be high and fairly constant. The measurements should not be made until the alternator has been run for a sufficiently long time to bring its bearings into good condition. Then the speed of the small motor should, by shunt control or otherwise, be adjusted at such a value as to drive the alternator at its rated speed. Suppose that the input to the small motor is then E volts and I amp., and that its efficiency at this input is 75 per cent. Then the friction and windage loss of the alternator amounts to $0.75 \times E \times I$. The field of the alternator should then be excited at constantly increasing values, and readings should be made of the volts and amp. input to the driving motor (whose speed must be maintained constant), and of the terminal voltage of the alternator on open circuit. This last reading permits of obtaining data for the saturation curve, during the progress of the core-loss test. If, at that value of the saturation corresponding to normal voltage of the alternator at no-load, the input to the driving motor is E_1 volts, and I_1 amp., and its efficiency under these conditions is 80 per cent., then the friction losses and the core loss together amount to $0.80 \times E_1 \times I_1$, and the core loss amounts to $0.80\, E_1 I_1 - 0.75\, EI$. The core loss at various other excitations should also be obtained.

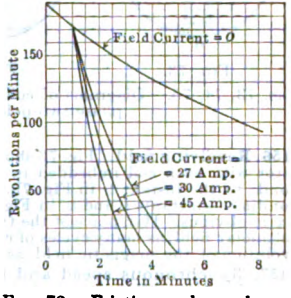


FIG. 72.—Friction and core-loss retardation curves of an alternator.

154. Retardation test for friction and core loss. The machine is brought up to speed and the driving belt or motor then disconnected. The machine then gradually decreases in speed, the speed being read on a tachometer at regular intervals, and a curve plotted showing the speed as a function of the time. If K is the moment of inertia of the rotating element in lb. ft.^{2} and S_1 and S_2 are successive speed readings in rev per min. at the beginning and end of a time T seconds; then when the field excitation is zero the friction losses in watts are given by the formula $P = [K \times 0.148(S_1^2 - S_2^2)] \div (2T)$. If the field is excited, the machine will come to rest in less time, and a larger loss P_1 will be obtained. This consists of the friction and core losses. By taking several curves with varying excitation, the core loss at different voltages may be determined, and a curve for core loss and voltage obtained. A typical set of retardation curves for a three-phase 350-kv-a., 2,100-volt, 50-cycle, 176-rev. per min. alternator is given in Fig. 72.

INDUCTION MACHINES

GENERAL THEORY OF THE POLYPHASE INDUCTION MOTOR

155. Principle of operation. The polyphase induction motor consists of a primary structure and a secondary structure. The former is usually stationary, supporting coils symmetrically on its inner periphery. These coils are displaced in space (*e.g.*, two coils at right angles, or three at 60 deg.), and in them flow currents of the same frequency, but differing symmetrically in phase, *e.g.*, two at 90 deg., or three at 60 deg.). The secondary (usually rotatable) structure carries properly displaced short-circuited coils. The polyphase currents in the primary structure produce a revolving field.*

* See any elementary text-book on this subject.

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As this cuts across the secondary conductors, currents are induced therein which, according to Lenz's law, are in such direction as to oppose the cause. That is to say, these secondary currents react on the revolving magnetic flux in such a way as to drag the secondary conductors and structure along with the rotating flux.

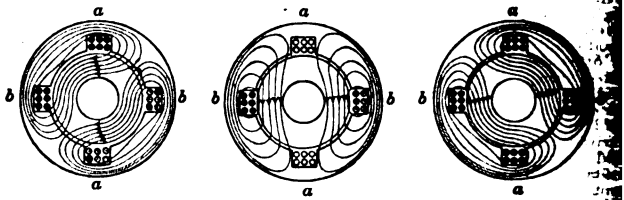


FIG. 73. FIG. 74. FIG. 75.

FIGS. 73, 74, 75.—Diagrams of coils and magnetic flux in elementary two-phase two-pole induction motor.

156. Revolving field. Fig. 73 shows a two-phase, two-pole, laminated-iron stator with each coil imbedded in a pair of slots. The flux shown corresponds to the instant t_1 in Fig. 76. Figs. 74 and 75 show the flux corresponding to instants t_2 and t_3 in Fig. 76. The rotation or progression of the flux is obvious. If in place of the two-pole field of Fig. 73, we substitute a multipolar field, as many cycles of current variation will be required for one revolution of the magnetic field, as there are pairs of poles.

157. Synchronous speed and slip. The speed of the revolving field is called the synchronous speed, and the percentage by which the speed of the rotor or secondary falls below this speed is called the slip. If $2p$ represents the number of poles, and f the frequency, the synchronous speed in rev. per min. is $R_s = 60f/p$.

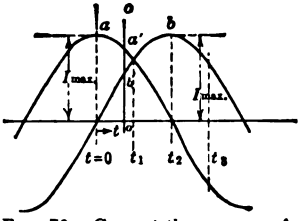


FIG. 76.—Current-time curves for two-phase indicator-motor windings.

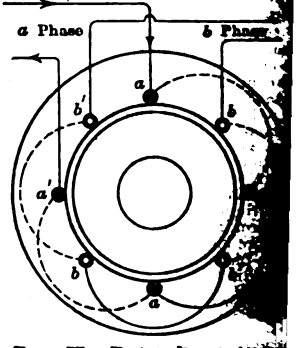


FIG. 77.—Four-pole, two-phase induction motor with one slot per pole per phase.

158. Induction motor similar to direct-current shunt-wound motor. Synchronous speed in an induction motor corresponds to that of a direct-current shunt-wound motor at which the counter e.m.f. is equal to the impressed e.m.f. In fact the mechanical characteristics of the two motors are practically identical, within their working range. For example, starting with the rotor at nearly synchronous speed, assume a load to be applied at the pulley. The speed will drop; the rate at which the secondary conductors cut (or *slip* backward through) the revolving field

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increase; and the induced e.m.f., the current and the torque will increase until the increase in torque just meets the demand imposed by the load. All of this is analogous to the operation of a shunt motor, but there is one important difference. In the induction motor, as the slip increases, the frequency and therefore the leakage reactance of the secondary increases in direct proportion. This results in an increasing lag of the secondary current behind the flux by which its e.m.f. is induced, and means, therefore, a decreasing effectiveness of the secondary current in torque production.

159. Stalling torque. Beyond a certain point, the increase of slip and slip voltage with load, is accompanied by an almost proportional increase of impedance, so that the secondary current ceases to increase with the slip at the same time that its torque effectiveness is decreasing. Thus there is a point or slip beyond which the torque actually decreases, causing the motor to stop. In a good motor this stalling torque is largely in excess of the torque at its rated load.*

160. Primary or stator winding. Fig. 77 shows a two-phase, four-pole stator with one slot per pole per phase.

161. Distribution of primary winding. On the score of tooth-tip or zigzag leakage (Par. 195), the concentrated or unicoil windings shown in

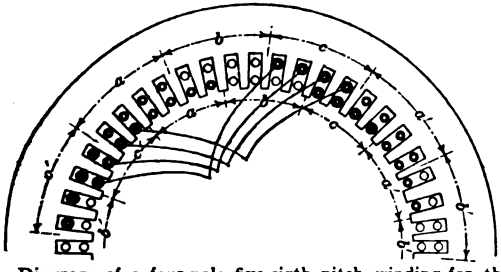


Fig. 78.—Diagram of a four-pole five-sixth pitch winding for the stator of a three-phase induction motor.

Figs. 73 and 77 are objectionable, and it becomes even more necessary than in the case of the synchronous machine, to distribute the winding among several slots per pole per phase, from two to eight or more, but rarely less than three.

162. Classification of stator windings. Stator windings correspond exactly with the armature windings of synchronous machines (Par. 16 to 22),

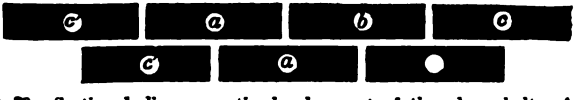


Fig. 79.—Sectional diagrammatic development of the phase belts of the winding of Fig. 78.

, as in that case, the two-layer lap winding is usually employed. Figs. and 79 relate to a three-phase, four-pole, two-layer lap winding, with five-ths pitch (ten slots in 12) and four slots per pole per phase. The bottom ed top slot belts labelled *a* comprise the back-connected (*down through*

* See provisions regarding stalling torque in the A. I. E. E. Standardization Rules (Sec. 24).

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the paper) conductors of the *a* phase, those labelled *a'* the out-ward c
nected (*up from* the paper) conductors of the same phase; similarly with
b and *c* phases. Several coil ends of the *c* phase are shown diagrammatica
Fig. 79 shows a diagrammatic developed end view of the phase belts.

A developed diagram of connections of the winding of Figs. 78 and 7
shown in Fig. 80, where the dotted lines indicate the bottom-slot coil sides
the lower layer.

163. Secondary or rotor windings. These may consist of any sy
metrical arrangement of short-circuited conductors in which series-connec
conductors do not generate opposing e.m.fs. There are three principal ty

(a) **Phase wound**, like the primary, except that the phases are sh
circuited or brought out through collector rings for insertion of start
resistance. The number of phases need not be the same as for the prima
and is usually 3.

(b) **Independently short-circuited loops or coils.** The two act
sides of each loop are approximately 180 magnetic deg. apart.

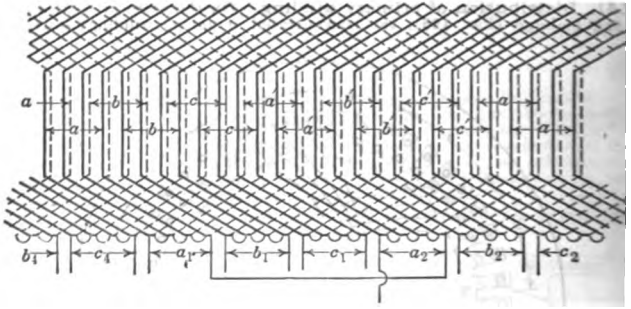


FIG. 80.—Developed winding diagram corresponding to Fig. 78 and Fig. 7

(c) **Squirrel cage**, consisting of conducting bars in slots, all connect
at the ends by conducting rings, called the end rings.

In (b) and (c) there are as many phases as there are slots per pole.

164. Peripheral distribution of current, m.m.f. and gap flux. T
cylindrical shell comprising the currents on the two sides of the air gap, a
the magnetic flux crossing the gap may be considered as the active reg
of any generator or motor, and the analysis of the phenomena in this reg
will yield most of the vital characteristics of the machine. Neglecting
localization of current in the slots and taking the average amperes per
of periphery in each phase belt, the heavy full-line curves of Fig. 81 show
primary current distribution of a three-phase full-pitch winding at
instants *m*, *n*, and *o* of Fig. 82. The axis of each curve in Fig. 81 rep
sents the air gap, and the sections *a*, *b*, *c*, etc., the primary phase be
along one side of the gap. The broken-line curves of Fig. 81 show
m.m.fs. around the flux paths crossing the gap at each point. That is,
maximum ordinate of the m.m.f. wave at *p* or *p'* is proportional to the amp
turns with which the longest flux path *pp'* (shown dotted) is linked. T
is the sum of the ampere-turns of belts *c'*, *a*, and *b*. Similarly the ordin
at *q* or *q'* represents the ampere-turns of the belt *a* with which the p
qq' links.

Neglecting the ampere-turns consumed in the iron part of these paths,
ordinates of the m.m.f. curve may be used to designate the magnetic poten
differences across the gap at the several points. But since the gap is norm
of constant radial depth, the broken-line curves may be used also to re
sent the flux-density in the gap, the disturbing effect of the slot open
being neglected. If the concentration of the current in slots be conside

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the *m.m.f.* curves would be of the step variety with a step for every tooth. Fig. 83 is the same as Fig. 81 except that the coil pitch has been reduced to five-sixths. In both Figs. 81 and 83, it will be observed that although the gap-flux-distribution curve changes its shape slightly, it is nearly sinusoidal, and that it progresses or rotates uniformly around the gap periphery. Sine-waves are shown for comparison. The shape of the current distribution curve changes more than that of the m.m.f. curve, but it progresses or rotates at the same velocity. The changes of the flux curve, in shape and magnitude, are graphically analyzed for full-pitch windings on pages 380–390 of the 2nd edition of Hobart's "Electric Motors." See also pages 120–

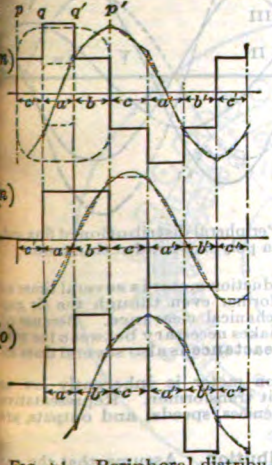


FIG. 81.—Peripheral distribution of primary current and m.m.f. in a three-phase, full-pitch stator.

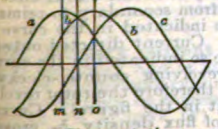


FIG. 82.—Current-time curves for a three-phase winding.

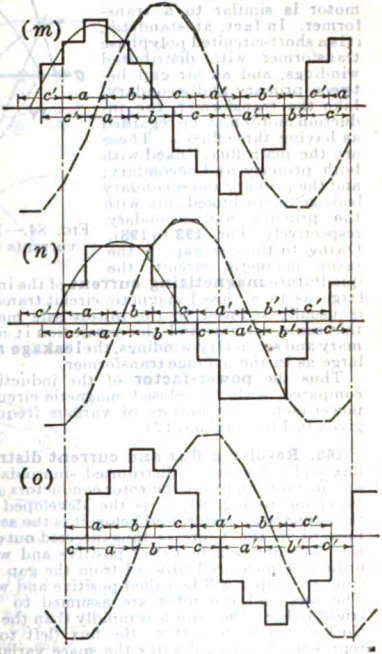


FIG. 83.—Peripheral distribution of primary current and m.m.f. in a three-phase, five-sixths pitch stator winding.

125 of Hobart's "Design of Polyphase Generators and Motors," especially the diagram on page 123.

165. Flux and current distribution for two-phase motors. In a two-phase motor the belts are broader, the steps in the current and flux-distribution curves larger and the change of shape from instant to instant greater. The breaking up of the belts by usng a five-sixths pitch in the three-phase, or a three-quarters pitch in the quarter-phase motor, reduces these variations and smooths out the curves.

166. Secondary current and m.m.f. relations. Since the secondary *m.m.f.* is induced by cutting the gap flux, the resulting secondary current will

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bear a definite space-phase relation to the gap flux (Fig. 84), and its m.m. will be sinusoidally distributed around the gap. Also, since the primary (s stator) counter *e.m.f.* is nearly equal to the impressed *e.m.f.* and is induced b the rotation of the gap flux at synchronous speed, the flux will be nearly co stant in magnitude, for constant impressed *e.m.f.* Thus the resultant of t primary and secondary *m.m.fs.* will be nearly constant and such as to produce the constant flux.

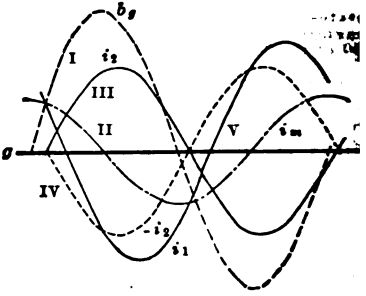


FIG. 84.—Peripheral distribution of flux an currents in polyphase induction motor.

167. Similarity of the induction motor to the transformer. Thus the induction motor is similar to a transformer. In fact, at standstill, it is a short-circuited polyphase transformer with distributed windings, and an air gap between primary and secondary. Like the transformer, the induction motor may be regarded as having three fluxes. These are the main flux, linked with both primary and secondary; and the primary and secondary leakage fluxes, linked only with the primary and secondary respectively (Par. 193 to 198). Owing to the air gap in the main magnetic circuit, the quadrature **magnetizing current** of the induction motor is several times a large as in a closed magnetic circuit transformer, even though the air ga is usually reduced to the lowest safe mechanical clearance. Because o this same air gap and the separation it makes necessary between the pri mary and secondary windings, the **leakage reactance** is also several times a large as in the average transformer.

Thus the **power-factor** of the induction motor is inherently low a compared with the closed magnetic circuit transformer. Representativ power-factors for motors of various frequencies, speeds, and outputs, ar given in Figs. 119 and 121.

168. Revolving flux and current distribution. Assume that the ga flux and currents are distributed sinusoidally around the gap periphery a any instant, and that the rotor conductors are independently short-circuited Referring to Fig. 84, *gg* is the developed air-gap line; above this line i the primary or stator, and below it is the secondary or rotor. Flux directe upward in the figure is thus directed outward from secondary to primary this direction will be called positive and will be indicated in the curve b ordinates measured upward from the gap line. Current directed outwar from the paper will be called positive and will be so indicated in the curve The flux and the rotor are assumed to be revolving counter-clockwis (right to left), the rotor less rapidly than the flux; therefore the rotor revolve clockwise with respect to the flux (left to right in the figure). Curve represents by its ordinates the space variation of flux density, b_g, crossin the gap. This sinusoidal flux distribution will be assumed as the startin point. Its magnitude is approximately constant and dependent upon th impressed e.m.f. as in the transformer. See also B_g in Fig. 85.

169. Magnetizing Current i_m. In order to supply the correspondin distribution of magnetic potential difference, there will be required a sinu soidal distribution of magnetizing current i_m, such as shown by curve *II* Fig. 84. See also I_m, Fig. 86. The *m.m.f.* (and therefore the flux) dis tribution must be the integral of the magnetizing-current distribution, an differ in space phase by 90 deg.

170. Secondary or slip e.m.f., e'_2. As the rotor conductors slip back ward (left to right, Fig. 84) through the flux, each will experience an e.m.f proportional (at fixed slip velocity) to the density of the flux at the positio in question. Curve *I* may therefore be used to designate at proper scale th

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e.m.fs., e'_2, induced in the several secondary conductors (plotted according to the positions of the conductors in which the e.m.fs. are induced) at any given instant. Curve *I* may also be used to designate the e.m.f. of a single conductor as it moves through the flux, plotted according to the position of that conductor with respect to the flux.

171. **The secondary current i_2** will have a time lag with respect to e'_2, because of the secondary leakage reactance; its curve will therefore be displaced to the right, curve *III*, Fig. 84, since each conductor will have moved with respect to the flux during the lag interval between the occurrence of corresponding values of e'_2 and i_2. See also I_2 in Fig. 85.

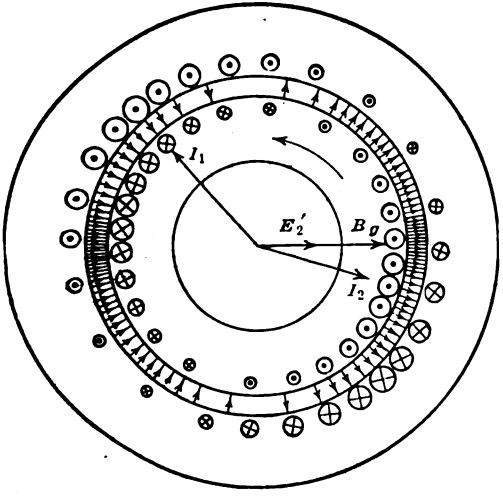


FIG. 85.—Semipictorial representation of vector quantities involved in induction-motor operation.

172. **Primary current i_1.** The primary current density at any point of the periphery and at any instant, must then be such as to neutralise the m.m.f. of the secondary current and also to supply the magnetizing current i_m. It will then be represented by Curve V which is the sum of i_m (Curve II) and $-i_2$ (Curve IV) at that same point and instant. See also I_1 in Fig. 85.

173. **Basis for vector diagram of induction motor.** It should be remembered that the curves of Fig. 84 represent primarily space distributions of the several variables at a given instant, and that these distributions revolve at synchronous speed around the gap periphery, keeping the same relative positions or space phases for a given condition of load. These distributions are shown in semipictorial fashion in Fig. 85, where the vectors B_g, I_2, and I_1 point to the positions at which the maximum positive values of these quantities occur, at the instant shown.

The time variation of all these quantities with respect to any particular point or conductor on the primary side of the gap, will be sinusoidal at primary frequency, and at secondary or slip frequency with respect to any point or conductor on the secondary structure. It is only from this point of view and with this understanding that it is possible to represent consistently primary and secondary variables on the same vector diagram.

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Thus the vectors of Fig. 85 may be used to represent not only the space phases, but also the time phases of the several variables, when viewed from either stationary or rotating structure, it being obvious that there is no fixed phase difference between the primary current in a particular *primary* conductor, and the secondary current of very different frequency in a particular *secondary* conductor. By extending the vector diagram of Fig. 85 we obtain the complete space and time vector diagram of the induction motor in Fig. 86.

174. Analysis of vector diagram. E'_1 is that part of the impressed e.m.f. to neutralize the counter e.m.f. induced by the mutual flux Φ, the direction of the vector Φ being that of the plane of the coil when it links the maximum flux, just as the direction of B_g is that of the plane of the coil when it is cutting the densest gap flux and generating the maximum e.m.f. I_m is the magnetizing current and I_{c+h} the core loss energy current, their

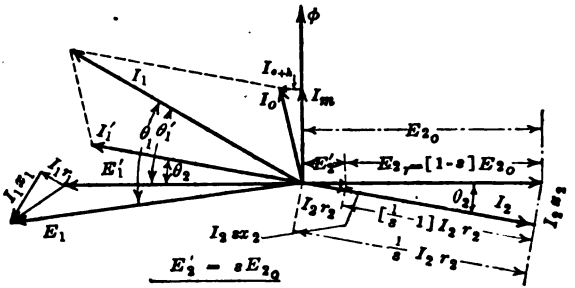


FIG. 86.—Vector diagram for induction motor.

sum being I_o, commonly called the exciting current. Assuming all secondary quantities reduced to primary turns, $E_{2_0} = E'_1$ is the e.m.f. that would be induced in the secondary at standstill. The actual secondary induced e.m.f. is E'_2, which equals sE_{2_0}, where s is the slip. $E_{2_r} = (1-s)E_{2_0}$, is the e.m.f. that would be induced in the secondary if revolving in the flux Φ at its actual speed, and will be called the speed e.m.f. x_2 is the secondary leakage reactance at primary frequency, and sx_2 the same at slip frequency. The secondary resistance is r_2. The secondary current is therefore:

$$I_2 = \frac{E'_2}{\sqrt{r_2^2 + s^2 x_2^2}} = \frac{E_{2_0}}{\sqrt{\left(\frac{r_2}{s}\right)^2 + x_2^2}} \quad \text{(amp.)} \qquad (37)$$

(The two e.m.f. triangles corresponding to these equations are shown in Fig. 86.) I'_1 is the part of the primary current to neutralize I_2, and I the total primary current. $I_1 r_1$ and $I_1 x_1$ are the e.m.fs. consumed by primary resistance and leakage reactance respectively. E_1 is the impressed e.m.f.

175. The corresponding "equivalent circuit" scheme is given in Fig. 87, which is exactly that of a transformer with a non-inductive load resistance $(r_2/s)(1-s)$.

176. Direct-current shunt-motor analogy. It is obvious that the speed voltage E_{2_r} consumed by the fictitious load resistance is the representative of the rotational power transformed, including output and friction losses, and is exactly analogous to the counter e.m.f. of a direct current motor. Similarly, E_{2_0} corresponds to the impressed e.m.f. and E_1 to the net or resistance consumed e.m.f. of the direct-current motor.

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177. Power analysis. The following analysis of the power P_1, delivered to the motor primary, may be readily followed from either Fig. 86 or Fig. 87. Designating the number of phases by p', the primary power per phase is

$$\frac{P_1}{p'} = I_1 E_1 \cos\theta_1 = I_1^2 r_1 + E'_1 I_1 \cos\theta_1$$

$$= I_1^2 r_1 + I_o x E'_1 + (E'_1 I'_1 \cos\theta_2 = E_{2_r} I_2 \cos\theta_2)$$

$$= I_1^2 r_1 + I_o x E'_1 + I_2^2 r_2 + E_{2_r} I_2 \cos\theta_2$$

$$= I_1^2 r_1 + I_o x E'_1 + I_2^2 r_2 + I_2^2 \left(\frac{r_2}{S}\right)(1-s) \text{ (watts)} \quad (38)$$

In words, P_1 = primary copper loss + core loss + secondary copper loss + output (including friction), and $P'_2 = p' E'_1 I'_1 \cos\theta_2 = p' E_{2_r} I_2 \cos\theta_2$ is the power transmitted across the air gap. P'_2 is the product of the torque of the revolving field by its angular velocity, or $P'_2 = 0.142 T R_o$ where T = torque in lb. ft. and R_o = rev. per min. at synchronism.

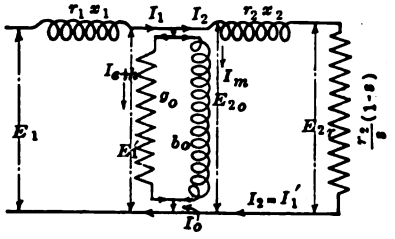


FIG. 87.—"Equivalent circuit" scheme for induction motor.

178. Torque. But the torque received by the rotor must be the same as that delivered by the revolving field, and neglecting friction, this is all delivered at the pulley. Thus the output (including friction) is $P_2 = 0.142 T R_r$ where R_r = rotor rev. per min.

$$P_2 = P'_2 \frac{R_r}{R_o} = (1-s)P'_2, \text{ and } P'_2 - P_2 = sP'_2 = p' I_2^2 r \text{ (watts)} \quad (39)$$

The slip is thus a measure of the secondary copper loss, and the motor is analogous to a friction coupling in which the friction torque between the two faces is proportional to the slip. Since R_o is constant, the torque is directly proportional to P'_2; in fact, P'_2 is frequently referred to as the torque in synchronous watts, meaning the power-equivalent of the torque at synchronous speed, measured in watts. Thus

$$T_{sw} = P'_2 = p' E_{2_r} I_2 \cos\theta_2 \text{ (watts)} \quad (40)$$

and

$$T = 7.05 \frac{P'_2}{R_o} = 7.05 p' E_{2_r} I_2 \cos\theta_2 \times \frac{1}{R_o} \text{ (lb. ft.)} \quad (41)$$

$IT = I_2 \cos\theta_2$ is called the torque current.

INDUCTION-MOTOR CHARACTERISTICS

179. Exact formulæ. From the vector diagram of Fig. 86 or from the equivalent circuit scheme of Fig. 87, exact formulæ may be easily developed for the currents, fluxes, voltages, powers, torque, power-factor, efficiency, etc., all in terms of E_1, s, and the constants of the motor; but these are such complicated functions of the slip as to be too cumbersome for quick computation, although none too accurate for poor motors. By a poor motor is not meant necessarily a poor design, but a poor result which may be due to difficult specifications, *e.g.*, relatively low speed or relatively high frequency.

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180. Approximate working formulæ for torque, output and starting current. For most purposes the following are sufficiently accurate. It will be observed that the constants of the exciting circuit do not enter; this is due to the approximation, which is equivalent to neglecting the exciting current as far as it affects the quantities considered.

Torque

$$T = \frac{7.05}{R_s} \frac{p' E_1^2 \frac{r_2}{s}}{\left(r_1 + \frac{r_2}{s}\right)^2 + (x_1 + x_2)^2} \quad \text{(lb. ft.)} \quad (42)$$

Slip corresponding to maximum torque

$$s T_{max} = \frac{r_2}{\sqrt{r_1^2 + (x_1 + x_2)^2}} \quad \text{(lb. ft.)} \quad (43)$$

Maximum or stalling torque

$$T_{max} = \frac{7.05}{R_s} \frac{p' E_1^2}{2\left[r_1 + \sqrt{r_1^2 + (x_1 + x_2)^2}\right]} \quad \text{(lb. ft.)} \quad (44)$$

Starting torque

$$T_s = \frac{7.05}{R_s} \frac{p' r_2 E_1^2}{(r_1 + r_2)^2 + (x_1 + x_2)^2} \quad \text{(lb. ft.)} \quad (45)$$

Starting current

$$I_s = \frac{E_1}{\sqrt{(r_1 + r_2)^2 + (x_1 + x_2)^2}} \quad \text{(amps.)} \quad (46)$$

$$T_s = \frac{7.05}{R_s} p' I_s^2 r_2 \quad (47)$$

r_2 corresponding to maximum starting torque

$$r_2 = \sqrt{r_1^2 + (x_1 + x_2)^2} \quad \text{(ohms)} \quad (48)$$

Output

$$P_2 = p' E_1^2 \frac{\frac{r_2}{s}(1 - s)}{\left(r_1 + \frac{r_2}{s}\right)^2 + (x_1 + x_2)^2} \quad \text{(watts)} \quad (49)$$

Maximum output, i.e., stalling load

$$P_{2max} = \frac{p' E_1^2}{2\left[(r_1 + r_2) + \sqrt{(r_1 + r_2)^2 + (x_1 + x_2)^2}\right]} \quad \text{(watts)} \quad (50)$$

Slip corresponding to maximum output

$$s P_{2max} = \frac{r_2}{r_2 + \sqrt{(r_1 + r_2)^2 + (x_1 + x_2)^2}} \quad (51)$$

These approximations are fairly accurate except where the exciting current is large. As the primary current and power-factor are both largely affected by the approximation involved in the formulæ given above, their formulæ are not given. They can be most easily obtained from the circle diagram.

181. The method of percentages. For the purpose of discussing the operating characteristics of an induction machine, as well as in connection with problems involved in its design, the following method of valuing its constants will be found very convenient. Referring to Figs. 86 and 88, and remembering that $E_{2_0} = E_1'$, let $I_1 r_1 / E_1' = q_{r_1}$; $I_1 x_1 / E_1' = q_{x_1}$; $I_2 r_2 / E_1' = q_{r_2}$; $I_2 x_2 / E_1' = q_{x_2}$; $q_s = q_{x_1} + q_{x_2}$. Let $I_2 \cos \theta_2 = I_T$ be called the torque current, since it is the component of I_2 which is effective in producing torque. $I_m / I_T = q_m$; $I_{e+h} / I_T = q_e$; $I_e / I_T = q_e$; $q = q_s + q_m$ = total quadrature component. $I_2 / I_T = q_2$; $I_1 / I_T = q_1$; $E_1 / E'_1 = q_{E_1}$; $T_{max} / T_f = q_{T_{max}}$

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where T_f = full-load torque; etc. All currents, voltages, etc., correspond to full-load unless otherwise specified. These could have been expressed in terms of E_1 and I_1 rather than in terms of E'_1 and I_T, but for most purposes the latter will be found more convenient. Formulæ for these percentages are given in Par. **182** to **189**. The torque formulæ given above, as well as many others involving vital relationships between induction-motor variables, may be written in terms of these percentages, with the advantage that while the actual constants r_1, x_1, etc., have values depending upon the size and voltage of the motor, and are not easily compared as between

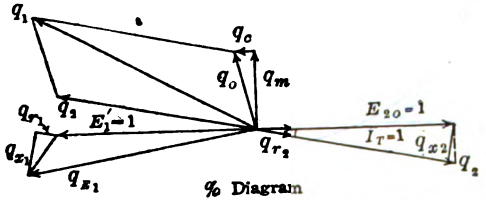


FIG. 88.—Percentage vector diagram for induction motor.

two motors of different voltages or outputs, the percentage values are immediately comparable and are direct measures of all the vital relationships. This advantage is particularly marked in the case of approximate formulæ. where their simplicity enables one to compute mentally most of the important characteristics of an induction motor, starting with only two or three of these percentages. Moreover, it is a very simple matter to memorize the range of these percentages in standard machines, as well as the effect of unusual specifications, and thus hold in one's head vital information concerning machines of all sizes and voltages, which would otherwise fill many long tables.

182. Power-factor. Referring to Fig. 88, the power-factor ($\cos \theta_1$) is obtained by resolving each vector along and perpendicular to E_1. The exact formula is complicated, but a fair approximation is

$$\text{power-factor} = \frac{1}{\sqrt{1+q^2}} \qquad (52)$$

In Fig. 89, curve III is plotted from Eq. 52 and curve I from the complete equation with the following assumptions; $q_{r1}=0.02$; $q_c=0.04$; and $q_{x1}=1.3q_{x2}$.

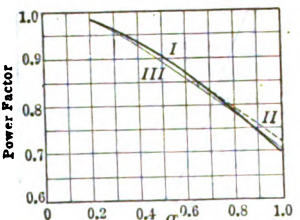


FIG. 89.—Power-factor plotted as a function of $q(=q_m+q_x)$, the total quadrature component.

183. Slip. $s = q_{r_2} \div \sqrt{1-q_{x_2}^2}$. But, in a reasonably good motor, q_{x2} is not more than 12 per cent., whence, for all practical purposes $s = q_{r2}$.

184. Stalling torque. Start with Eq. 44 and assume as average values for a good motor of moderate size: $q_{r_1}=0.02$; $q_{x_1}=0.12$; $q_{x_2}=0.09$; $q_x=0.21$; $q_m=0.25$; $q_c=0.04$. Then it can easily be shown that if T_f is the full-load torque, the per cent. maximum or stalling torque is

$$q_{T_{max}} = T_{max} \div T_f = 1 \div (k_T q_x) \qquad \text{(approx.)} \qquad (53)$$

where k_T varies from 1.85 for a motor with high, to 2 in a motor with low

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power-factor. T_{max}/T_f is plotted against q_x in Fig. 90, for $k_T = 1.9$. Fro which, if 2 is the lower limit for T_{max}/T_f, q_x must not be more than 0.26.

185. Per cent. stalling torque. Hobart gives the per cent. stalli torque in terms of σ (Par. 207) and q_m as follows ("Polyphase Generators a

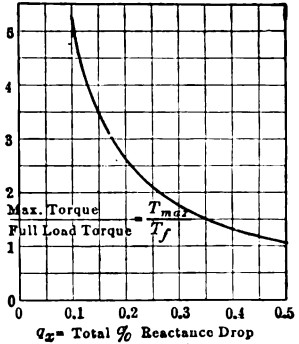


FIG. 90.—Ratio of maximum torque to full-load torque, plotted as a function of the total percentage reactance drop.

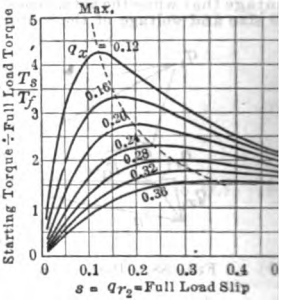


FIG. 91.—Ratio of starting torqu to full-load torque.

Motors," page 190): $qT_{max} = 0.4\ q_m/\sigma$. This is equivalent to $k_T = 2.3$, (sinc $\sigma = 0.93\ q_m q_x$), which is considerably larger than 1.9 used in Fig. 90.

186. Starting torque. Beginning wit Eq. 45, it can be shown that the per cen starting torque is

$$qT_s = T_s \div T_f = \frac{1.20 q_{r_2}}{(q_{r_1}+q_{r_2})^2+q_x^2} \quad \text{(approximately)} \qquad (54$$

Assuming $q_{r_1} = 0.02$, the ratio T_s/T_f plotted against q_{r_2} in Fig. 91, for severa values of q_x within the range of commer cial motors; from which the quantitativ limitations in the starting torque of th induction motor are obvious. The maxi mum value of the ratio T_s/T_f is obvious the same as T_{max}/T_f and occurs when q is about equal to q_x.

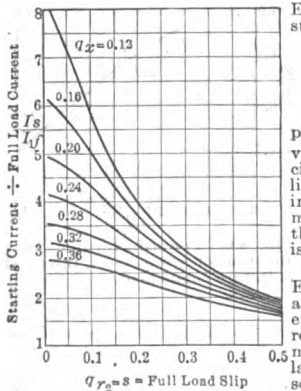


FIG. 92.—Ratio of starting current to full-load current, plotted as a function of the full-load slip.

187. Secondary starting resistance Except in machines of very low reactanc a large starting torque is only possible b employing a comparatively large secondar resistance. In a squirrel-cage motor thi means large secondary copper loss an large slip. The desirable resistance of squirrel-cage secondary is usually a com promise between the low-resistance neede for speed regulation and efficiency, and th high resistance desired for starting torque the relative weight given to these two con siderations being determined by the speci fications. In a wound-rotor machine, resistance can be inserted in the sec ondary for starting and cut out after the machine has attained speed.

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188. Starting current. Neglecting the exciting current, the starting current is given by Eq. 46; this may be transformed to

$$I_s = I_T \frac{1.1}{\sqrt{(q_{r_1}+q_{r_2})^2+q_x^2}} = \frac{I_{1f}}{\sqrt{q_r^2+q_x^2}} \quad \text{(approx.) (amp.) (55)}$$

or

$$q_{I_s} = I_s + I_{1f} = 1 \div (\sqrt{q_r^2+q_x^2}) \quad (56)$$

The ratio (I_s/I_{1f}) of the starting current to the full-load primary current is plotted against q_{r_2} for several values of q_x in Fig 92; q_{r_1} is again taken =0.02. It will appear from an inspection of Fig. 92 that the starting current taken by a squirrel-cage induction motor at full voltage is too large to be tolerated in the case of large motors. In such cases compensators or induction starters are used to reduce the voltage during the starting period.

189. Compensator starting of squirrel-cage motors. To find the per cent. starting torque for a given maximum allowable line current, let T_{sc} = starting torque with compensator; T_f = full-load torque; I_l = line current at starting and I_f = full-load current.

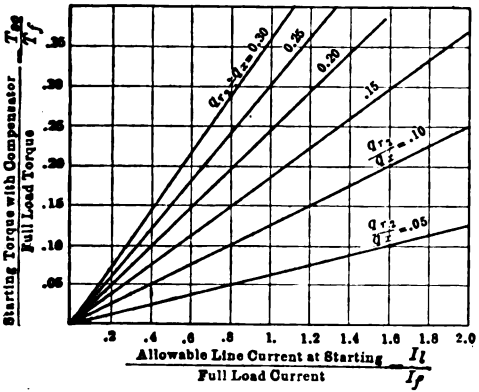


FIG. 93.—Torque relations when starting with induction starter or compensator.

Then from Eq. 54 and 56 and the compensator relations, it can be shown that

$$q_{T_{sc}} = \frac{T_{sc}}{T_f} = \frac{I_l}{I_f} \frac{1.25q_{r_2}}{\sqrt{q_r^2+q_x^2}} \quad \text{(approx.)} \quad (57)$$

This is plotted in Fig. 93 for several values of the ratio (q_{r_2}/q_x). As an example, take a large squirrel-cage motor which must be started without drawing more than full-load current from the line. Assume $q_x = 0.20$ and $q_r = 0.02$. Then $T_{sc}/T_f = (1.25 \times 0.02)/0.201 = 0.124$ or one-eighth of full-load torque.

190. Deep rotor bars for starting. The curves of Figs. 91 to 93 show in a striking manner the inherently poor starting qualities of squirrel-cage induction motors, except when a large full-load slip is allowed. This defect may be eliminated in some degree by a very ingenious device consisting in the use of very deep rotor slots and bars, which gives a high apparent resistance and low reactance at starting, and the reverse near synchronism. The only drawback is the reduced stalling torque; but in many cases there is ample margin. The resistance multiplier is 0.35 × depth of bar in inches × $\sqrt{\text{frequency}}$. See Hobart's "Design of Polyphase Generators and Motors," p. 168.

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191. Summary. Figs. 89 to 93 show clearly the relations of all th vital operating characteristics (except heating) of induction motors c whatever size, frequency, or voltage, to a very few constants; and althoug the results are only approximate, they will give a fair quantitative gras of induction motor characteristics. The largest errors will occur in small c low-speed motors with large exciting currents.

The most important of these characteristics are almost wholly determine by q_m, q_s, and q_{r_2}. The other q's may be approximated with sufficien accuracy, since they play only a small part, and a considerable error in thei approximation does not seriously affect the results. Of q_m, q_s, and q_{r_2} th last may be given almost any desired value without much affecting the othe constants; whereas q_m, and q_s are intimately related to one another, to th major design constants, and to the details of design. Their computatio is given below.

MAGNETIZING CURRENT*

192. Air gap and gap ampere-turns. The air gap is usually reduce to a comfortable mechanical clearance, and may be taken approximatel as $\delta = 0.015\sqrt[4]{\text{kw.}}$ (inches). The gap ampere-turns are computed in th same manner as for the alternator (see Par. 40, Figs. 39 and 40). Designate b a_1 and a_2, respectively, the primary and secondary slot-contraction factors by $K_1 = a_1 a_2$, the combined slot-contraction factor; by K_d the correspondin air-duct contraction factor; and by K_2 the ratio of gap ampere-turns to tota ampere-turns. K_2 varies from 0.9 in slow-speed high-frequency machine to 0.7 in high-speed, low-frequency machines. These are, however, outsid limits, and 0.8 may ordinarily be assumed as a fair average for a roug approximation. Then the total ampere-turns for the longest complete mag netic circuit is $Ni_l = (0.626\mathfrak{B}\delta)/K_1K_2K_d$.

Let Δ = peripheral loading corresponding to torque current I_T (Fig. 88) $\mathfrak{B}$ = maximum or crest value of equivalent sine-wave of gap-flux distribution; v = peripheral velocity (ft. per sec.) of revolving field; for k_b and k_p see Par. 28–31 (synchronous machines).

Then, assuming that the magnetizing current is equivalent to a sinusoidal distribution of current density, of root-mean-square value Δ_m, $\Delta_m = 0.116\mathfrak{B}\delta f/(k_b k_p K_1 K_2 K_d v)$ and the per cent. or fractional magnetizing current is

$$q_m = \Delta_m/\Delta = 0.116\mathfrak{B}\delta f/(k_b k_p K_1 K_2 K_d \Delta v) \qquad (58)$$

For a three-phase motor $k_b = 0.955$. For five-sixths pitch $k_p = 0.96$. Fo open-slot stator and nearly closed-slot rotor, $K_1 = 0.65$ (approx.). For well-ducted motor $K_d = 0.9$. For a 60-cycle motor, $K_2 = 0.8$ (approx.) Then, roughly, $q_m = (0.27\mathfrak{B}\delta f)/(\Delta v)$.

LEAKAGE REACTANCE*

193. The four elements of the leakage flux are computed as if separate from the main flux, whereas they are for the most part only distor tional as to the main flux. Consider the phase-belt as the unit, Figs. 94 and 95.

194. Slot leakage.* This is the cross-slot flux (Fig. 94). The inch per-

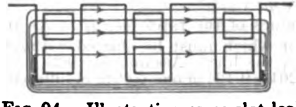


FIG. 94.—Illustrating cross-slot leakage flux.

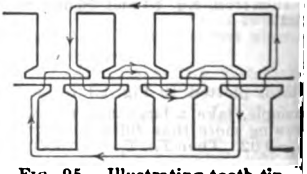


FIG. 95.—Illustrating tooth-tip leakage.

meance or flux linkage (lines) per amp. in. of primary phase-belt is (s Fig. 42)

$$\varphi_{sb1} = \frac{3.2}{N_{spp}}\left(\frac{1}{3}\frac{d_1}{w_s} + \frac{d_2}{w_s} + \frac{2d_3}{w_s + w_{so}} + \frac{d_4}{w_{so}}\right) \qquad (5$$

*Transactions American Institute Electrical Engineers, Vol. XXIV, 19 p. 338. Also Vol. XXVI, p. 1245.

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The total slot-linkage per amp. in. of phase-belt is

$$\varphi_{sb} = \varphi_{sb1} + \varphi_{sb2} \qquad (60)$$

where N_{spp} = slots per pole per phase, and N_s the number of slots.

195. Tooth-tip or zigzag leakage. See Fig. 95. The flux linkage (lines) per amp. in. of belt, for both primary and secondary is $\varphi_{tb} = A\tau_t \div \delta N_{spp}$ where τ_t is the average tooth pitch, primary and secondary, and $A = 2.13[(a_1 + a_2 - 1)/2]^2$ is plotted in Fig. 96.

The above values of φ_{sb} and φ_{tb} are for *full-pitch* and should be multiplied by k_{ps} and k_{pt} respectively (Figs. 97 and 98) for *fractional pitch* windings.

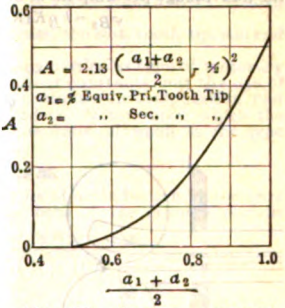
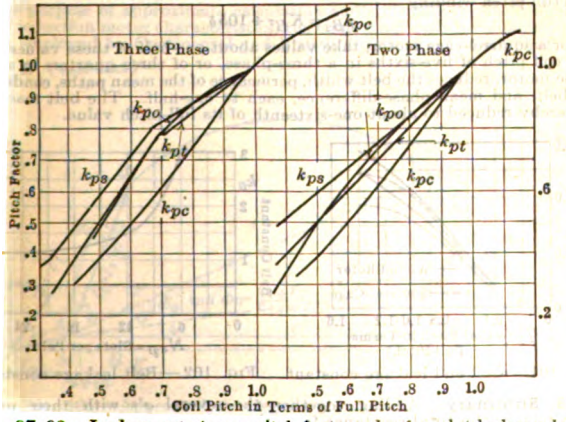


FIG. 96.—Average per cent. tooth-tip overlap "A," vs. average per cent. equivalent tooth-tip.

196. Coil-end leakage. A crude but helpful picture of this flux is shown in Fig. 99. Charging all coil-end leakage to the primary, the resulting lines per amp. in. of phase belt bundle, φ_f, is given in Fig. 100 for three-phase motors with various coil pitches, both for squirrel-cage and phase-wound rotors.

When reduced to the basis of the active phase-belt, φ_f becomes $\varphi_{fb} = k_3 k_f \varphi_f = k_3 K_f$ where k_f = ratio of length of one coil end to pole pitch, $k_3 = \tau/l$, and K_f $(= k_f \varphi_f)$ is plotted in Fig. 101 against the coil pitch, for squirrel-cage and wound-rotor motors. The higher values correspond to high-voltage machines where the coil overhang is longer, or to machines with the coil ends bent back, thus allowing more room for leakage between primary and secondary coil ends (Fig. 99). In the case of the squirrel-cage rotor, φ_f depends upon the type and position of the end ring.



FIGS. 97, 98.—Leakage-reactance pitch factors; k_{ps} for slot-leakage, k_{pt} for tooth-tip leakage, k_{pc} for coil-end leakage.

For a simple ring at the ends of the bars, the lowest value of φ_f corresponds to a position out from the core, equal to seven-tenths of the primary coil projection. That is, the primary coil-end currents act like a single circumferential current at the seven-tenths point (see the cross in Fig. 99, which

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indicates a circumferential current backward through the paper). If the ring is set radially inward nearer the shaft, φ_f may be increased as much as 50 per cent. (see the upper curve). Or, if the end ring is placed nearer the core, φ_f may be considerably increased (25 or 30 per cent.).

197. Belt-leakage.* For three-phase motors and full-pitch windings the flux linkage per amp-in. of belt is

$$\varphi B_3 = k_B K_1 K_2 K_{d\tau} + 314\delta = K_{B\tau} + 314\delta \qquad (61)$$

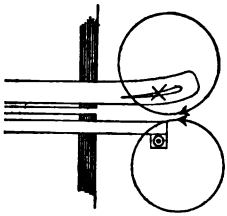


FIG. 99.—Coil-end leakage paths.

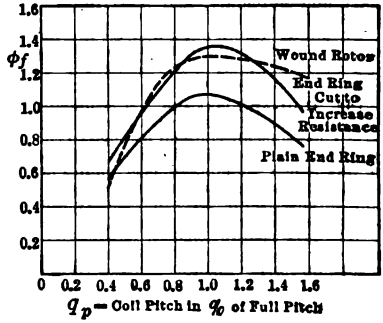


FIG. 100.—Coil-end flux linkage lines per ampere-inch of phase-belt bundle (primary and secondary) as a function of the coil pitch.

where k_B is given in Fig. 102 and $K_B = k_B K_1 K_2 K_d$. For a two-phase motor with full-pitch winding

$$\varphi B_2 = K_{B\tau} + 105\delta \qquad (61a)$$

For a squirrel-cage motor, take values about one-half of these values.

A coil pitch of five-sixths in a three-phase, or of three quarters in a two-phase motor, reduces the belt width, permeance of the mean paths, conductors per belt, and mean phase-difference, each to one-half. The belt reactance is thereby reduced to about one-sixteenth of its full-pitch value.

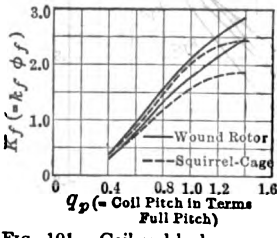


FIG. 101.—Coil-end leakage constant.

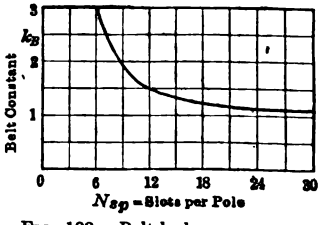


FIG. 102.—Belt leakage constant.

198. Summary. Adding together the several φ's with their proper pitch factors the total reactance for a three-phase motor is

$$x_3 = 2\pi f 2pl N^2_{cpp} 10^{-8} (k_{p\sigma}\varphi_{s\delta} + k_{p\varphi}\varphi_{b\delta} + k_3 K_f + K_{B\tau} + 314\delta) \qquad (62)$$

where N_{cpp} = conductors per pole per phase.

* See *Transactions* International Electrical Congress, St. Louis, 1904; Vol. I, page 706.

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resistance varied (variable s), the locus of the current is a circle. The excit ing current must be added to obtain the total current.

The corresponding diagram is shown in Fig. 104. If this diagram b rotated counter-clockwise until E_1 is slightly below the horizontal on th left, it will correspond with the left-hand side of the regular vector diagram Fig. 86. The diameter of the circle in Fig. 104 is $E_1/(x_1+x_2)$. B_s is th short-circuit or standstill point; tan $\varphi_s = \dfrac{r_1+r_2}{x_1+x_2}$, and $B_sG_s+G_sH_s = r_2+r_1$.

The approximation involved in this diagram is such that serious error are not introduced in the case of a good motor, *i.e.*, a motor with low excitin current and low reactance; but the errors become serious in poor motors.

200. Note concerning interpretation of approximate circle diagram. In what follows E_1 and I_1 are the volts and amperes of a single phase. If E_1 be the line voltage multiplied by $\sqrt{3}$, and I_1 the line current, p' should be omitted from all expressions for power and torque.

201. The impressed power is, $P_1 = p'E_1I_1 \cos\theta_1 = p'E_1 \times \overline{BK}$; but since $p'E_1$ is constant, $\overline{BK}$ is proportional to and a direct measure of the power delivered to the motor; *i.e.*, a scale of watts or kilowatts can be chosen according to which $\overline{BK}$ indicates directly the impressed power, P_1.

202. Losses, output, torque and slip. According to the same scale $\overline{HK}$ indicates the core loss, $p'E_1I_{e+h} = P_{e+h}$. If I_0 is measured when the motor is running light, the corresponding power will include the friction loss, in addition to core loss, and since the friction loss is practically constant,

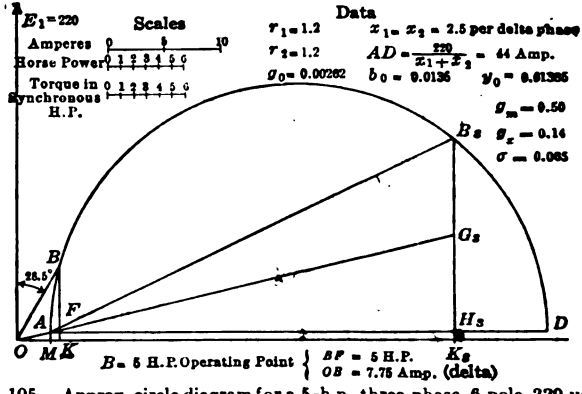


FIG. 105.—Approx. circle diagram for a 5-h.p. three phase, 6-pole, 220-volt, delta-connected induction motor.

it could be charged to the exciting circuit (Fig. 103), by increasing g_e in the proper degree. It will be so taken here, *i.e.*, that $\overline{HK}$ represents core and friction loss. Similarly $\overline{IIG}$ represents the primary copper loss, $\overline{GF}$ the secondary copper loss, $\overline{FB}$ the output (P_2), $\overline{GB}$ the power transmitted across the air gap (*i.e.*, the torque in synchronous watts) and $\overline{GF}+\overline{GB}$ the slip.

203. Efficiency (Par. 210–216). The efficiency is $P_2/P_1 = BF/BK$.

204. Power-factor (Par. 216). The power-factor, $\cos\theta_1$, may be readily determined from the diagram by drawing a unit circle about O and measuring the vertical intercept of the I_1 vector on this unit circle.

Thus for any point B on the circle, all the important variables of the induction motor may be readily determined from the circle diagram.

205. Experimental determination of circle diagram. The experimental data necessary is,

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(a) Amperes and watts at normal voltage when the motor is running light. This gives the $I_0 = \overline{OA}$ of Fig. 104. Thus the point A may be located, starting with O as the origin, and E_1 vertical.

(b) Amperes and watts at normal voltage with rotor blocked. It is sometimes necessary to make this test at reduced voltage owing to the excessive currents which would flow at full voltage, and to change the results to the full voltage equivalent. This will locate the point B_s, which together with A determines the circle, the diameter being assumed horizontal through A.

(c) The resistance of the primary winding.

All of these tests, particularly the last two, should of course be made at or near the normal working temperature of the motor.

The diagram thus experimentally determined, expresses with a very fair degree of accuracy the relations between all the important variables of the motor.

Fig. 105 shows the approximate circle diagram drawn to scale for a 5-h.p., three-phase, 6-pole, 200-volt, 60-cycle induction motor, and Fig. 106 shows the characteristic curves obtained therefrom.

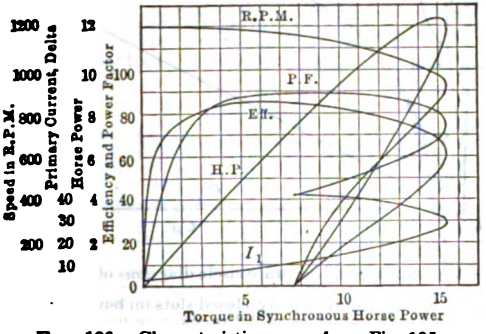


FIG. 106.—Characteristic curves from Fig. 105.

206. Exact circle diagram. Starting with the complete equivalent circuit scheme (Fig. 87), it is easy to prove that the locus of the primary current is a circle whose radius is $E_1/2x_d$, and the coordinates of whose centre with respect to O, are $E_1 b_c$ and $E_1 g_c$, where

$$x_d = x_1 + x_2 + \frac{x_1^2}{z_0^2}(x_0 + x_2) + \frac{2x_2}{z_0^2}(r_1 r_0 + x_1 x_0) \quad \text{(ohms)} \quad (63)$$

$$b_c = \frac{\frac{1}{2} + b_0 x_2}{x_d} + \frac{x_1(b_0 + x_0/z_0^2)}{x_d} \quad \text{(mhos)} \quad (64)$$

$$g_c = \frac{g_0 x_2}{x_d} + \frac{r_1(b_0 + x_0/z_0^2)}{x_d} \quad \text{(mhos)} \quad (65)$$

$E_1 b_c$ is the abscissa and $E_1 g_c$ the ordinate of the centre, starting with E_1 vertical. The approximate and accurate circle diagrams of a good motor are shown to scale in Fig. 107, both computed from the same constants. If the points B_s and A are determined experimentally, then the only inaccuracy of the approximate circle, is due to the fact that its centre would be located on the horizontal line through B_0 rather than at the real centre, which is usually a little above the line, see Fig. 107, where the broken-line circle was drawn through B_0 and B_s (observed), with centre C_A on horizontal line through B_s. Fig. 107 also shows the loci of the other variables.

207. Leakage factor or circle ratio. This is defined in various ways by various authors. Roughly it is the ratio of the total leakage permeance to the main flux-path permeance, or the ratio of the magnetising current to the diameter of the circle. Sometimes it is stated as the ratio of magnet-

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ising current to the short-circuit current, but this is inaccurate for motors with high secondary resistances. It is dependent upon the machine proportions and independent of the load.

For all practical purposes it is

$$\sigma = 0.93 q_m q_s = \frac{3.95 S \delta}{\tau^2} + \frac{3.95 A}{N_{ep}^2} + \frac{1.32 K_f \delta}{l} + 0.0052 \qquad (66)$$

For values of S, A and K_f see Par. **195** to **198** and Figs. 96 to 101. S varies from 6 to 18 with an average of 10 to 12; A from 0.2 for open slots

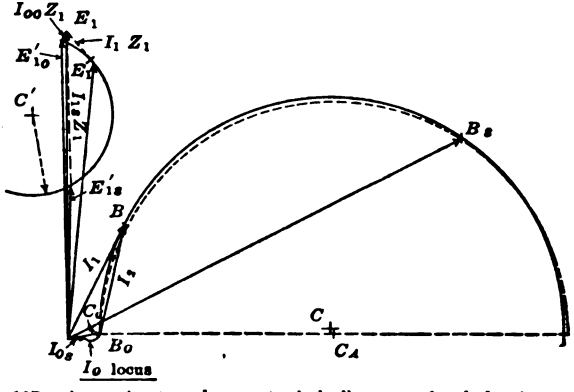


FIG. 107.—Approximate and accurate circle diagrams of an induction motor.

on one side of gap to 0.42 for nearly closed slots on both sides, and K_f from 1.5 in good squirrel-cage motors to 2.2 in slip ring motors, see Fig. 101.

Kierstead has proposed a somewhat simpler though less rational formula; it is

$$\sigma = C \left(\frac{0.079}{l} + \frac{0.19}{\tau} + \frac{3}{N^2_{ep}} \right) \qquad (67)$$

where C varies with the air gap according to the accompanying table

δ	0.024	0.032	0.039	0.047	0.055	0.063	0.071	0.079	0.087	0.095
C.....	0.71	0.88	0.99	1.09	1.17	1.25	1.31	1.39	1.45	1.52

Of these equations, Eq. 66 gives results quite as accurate as the average test results can check, and for all types of machines. Eq. 67 gives fair results for the majority of standard machines, although inaccurate for extreme cases.

The leakage factor or circle ratio is much used by European designers. Reference may be made to Hobart's "Electric Motors" and "Design of Polyphase Generators and Motors" where the designing of induction motors is explained with the assistance of the circle diagram in a simpler though less accurate manner than is described in Par. **243** to **269** below.

208. Maximum power-factor. In terms of σ, it is given by various authors, thus

$$\text{Maximum power-factor} = \frac{1}{1+2\sigma} \qquad (68)$$

$$\text{Maximum power-factor} = \frac{1-\sigma}{1+\sigma} \qquad (69)$$

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The accuracy and meaning of either of these depend upon the method of determining or of defining σ.

209. Bibliography of articles relating to the calculation of circle ratio.

I. Chapter IV (p. 29) of Behrend's "Induction Motor."

II. "The Magnetic Dispersion in Induction Motors," by Dr. Hans Behn-Eschenburg; *Jour.* I. E. E., Vol. XXXII (1904), pp. 239 to 294.

III. Chapter XXI on p. 470 of 2d Edition of Hobart's "Electric Motors."

IV. "The Leakage Reactance of Induction Motors," by A. S. McAllister, *Elec. World* for Jan. 26, 1907.

V. "The Design of Induction Motors," by Comfort A. Adams, *Trans.* A. I. E. E., Vol. XXIV (1905), pp. 647 to 687.

VI. "The Leakage Factor of Induction Motors," by H. Baker and J. T. Irwin, *Jour.* I. E. E., Vol. XXXVIII (1907), pp. 190 to 208.

LOSSES AND EFFICIENCY

210. Classification of losses. The losses of an induction motor are as follows: (a) the primary copper loss; (b) the secondary copper loss; (c) the core loss; (d) friction and windage losses. The copper losses may be computed in the ordinary way, except that in the case of squirrel-cage rotors the method is not quite so obvious. See Par. **212**, also Sec. 24.

211. Primary copper loss. In terms of the design constants and in terms of the output, it is

$$q_{r1} = \frac{(1+k_2k_f)10^6}{8.5k_3k_pmB_m} \qquad (70)$$

where m is the circ. mils per amp. Owing to the lower flux density in the gap, there is a greater length of active conductor than for the synchronous alternator; but this is partly neutralized by the larger m made necessary by the poorer ventilation of the short air-gap machine.

212. Secondary copper loss. In the case of a wound secondary, the copper loss is about the same as for the primary, for although the current is less, there is in most cases less slot section available for copper. In the case of a squirrel-cage rotor, it is usually easy to make the secondary resistance low. Unfortunately this opportunity may not ordinarily be taken advantage of, since the starting torque requirements frequently demand a relatively large value of the slip and therefore of q_{r2}, Par. **186** and Fig. 91.

The squirrel-cage copper loss may be computed as follows: The secondary current per bar is $I_b = \Delta_2 \tau_{t_2}$ where Δ_2 is the secondary peripheral loading and τ_{t_2} the secondary tooth pitch. I_b^2 times the ohms per bar times the number of bars = total bar loss. The current in each end ring is $I_r = I_b$ times the number of rotor conductors per pole divided by 2.22, and the end ring loss is I_r^2 times total series resistance of both end rings.

213. Core losses. The calculation of the core losses of an induction motor is not so simple a matter as might at first appear, since, in addition to the losses in core and teeth at fundamental frequency, there are tooth frequency losses in both primary and secondary teeth, wave losses in tooth tips and losses due to breakdown of laminations. There are also sometimes, at load, eddy losses in the copper conductors. See A. I. E. E., Vol. XXIV, p. 761.

214. Calculation of core losses. There is no simple *rational* method at present available for computing the core losses of induction motors with reasonable accuracy. The following formulæ have coefficients such that when applied to the primary teeth and core, they yield results large enough to cover the indeterminable losses, except in those cases where the tooth-frequency losses are unusually large, as with open slots on both rotor and stator.

For 60 cycles—Watts per cu. in. $= P_{60}' = 4.1(B_m/10^4)^2$.

For 25 cycles—Watts per cu. in. $= P_{25}' = 1.3(B_m/10^4)^2$. Laminations assumed to be 0.014 in. thick. Nearly all the extra losses are due to eddy currents rather than to hysteresis; hence the exponent 2 is sufficiently accurate.

The following table of data for estimating the core loss of induction motors is taken from Hobart's "Design of Polyphase Generators and Motors."

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Density in stator core (lines per sq. in.)	Core loss in stator core (watts per lb.) for various frequencies		
	$f = 15$	$f = 25$	$f = 50$
39,000	0.50	1.00	2.27
52,000	0.77	1.36	3.36
65,000	1.00	1.81	4.54
78,000	1.18	2.36	
90,000	1.45	2.81	

STANDARD POLYPHASE INDUCTION MOTORS

215. Representative power-factors and efficiencies of standard squirrel-cage motors. The losses and efficiency of a typical 5 h.p.

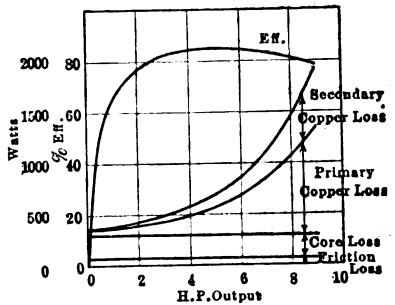


FIG. 108.—Losses and efficiency of a 5-h.p., 60-cycle squirrel-cage induction motor.

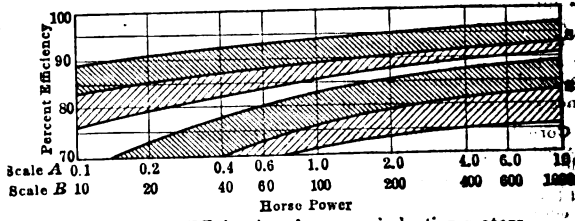


FIG. 109.—Efficiencies of average induction motors.

For Usual No. of Poles
Very Large No. of Poles

Note: In General, the smaller the No. of Poles, and the Higher the Frequency, the Higher the Efficiency. For 2 Poles, Efficiency may be Slightly above Upper Limit

60-cycle, squirrel-cage induction motor are shown plotted against the c... in Fig. 108. The efficiencies of average induction motors are p... in Fig. 109. While in any concrete case the designer has the powe... and the efficiency within his control to a certain extent, he cannot ... widely from representative values which are inherent to the ra... table in Par. 216 is adapted from more elaborate tables on pp. 11...

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117 of Hobart's "Design of Polyphase Generators and Motors" (McGraw Publishing Co., New York, 1913) and give representative values for the power-factor and efficiency of polyphase squirrel-cage motors of outputs ranging from 10 h.p. up to 1,000 h.p. and for a wide range of speeds corresponding to frequencies of 25 and 60 cycles, per sec.

216. Table of representative efficiencies and power-factors of moderate-voltage polyphase squirrel-cage induction motors at their rated loads

Frequency (cycles per sec.)	Synchronous speed (rev. per min.)	10 h.p.		50 h.p.		100 h.p.		500 h.p.		1,000 h.p.	
		Efficiency (per cent.)	Power-factor	Efficiency (per cent.)	Power-factor	Efficiency (per cent.)	Power-factor	Efficiency (per cent.)	Power-factor	Efficiency (per cent.)	Power-factor
25	188	75	0.76	81	0.80	87	0.83	90	0.85	91	0.87
	375	79	0.82	85	0.85	89	0.87	92	0.89	93	0.90
	750	83	0.88	88	0.91	91	0.93	93	0.94	94	0.95
60	450	75	0.75	84	0.79	89	0.82	91	0.84	93	0.86
	900	81	0.83	87	0.86	91	0.87	94	0.88	95	0.89
	1,800	85	0.90	90	0.92	93	0.93	95	0.93	96	0.93

217. Very large squirrel-cage motors. The properties and costs of 1,000-h.p. 25-cycle squirrel-cage three-phase motors have been investigated for five different speeds, in order to bring out clearly the dependence of the characteristics and cost upon the rated speed. The results are set forth in the following table which is taken from p. 105 of Hobart's "Electric Propulsion of Ships" (D. Van Nostrand, New York, 1911):

1,000-h.p., 25-cycle, squirrel-cage, three-phase motors

Speed, rev. per min.	Number of poles	Air-gap diameter (cm.)	Gross length of rotor core (cm.)	Max. power-factor	Total works cost in dollars (pre-war basis)
125	24	238	53	0.93	5,000
250	12	180	66	0.94	3,800
375	8	138	76	0.95	3,200
500	6	114	83	0.96	2,840
750	4	87	95	0.96	2,500

From the same source ("Elec. Prop. of Ships") is taken the data in the following two tables, the first relating to designs worked out by one of the present authors for three 25-cycle, 125-r.p.m., 24-pole squirrel-cage induction motors for outputs of 100 h.p., 1,000 h.p. and 10,000 h.p., respectively, and the second relating to the complete weight, in metric tons, of five large motors. The costs are based on pre-war figures.

Data of three 25-cycle, 125-r.p.m., 24-pole squirrel-cage induction motors

Rated output (h.p.)	100.	1,000.	10,000.
Air-gap diameter (c.m.)	151.	288.	565.
Gross core length (c.m.)	28.	53.	104.
Maximum power-factor	0.90	0.93	0.91
Peripheral speed (m. per sec.)	9.8	18.8	37.
Total works cost (dollars)	950.	5,000.	21,000.
Total works cost per horse-power	9.50	5.0	2.10
Total weight (metric tons)	3.5	14.	80.

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Data of complete weight (exclusive of shaft and bearings) of five 33-cycle squirrel-cage induction motors for a synchronous speed of 124 r.p.m.

Rated output	Weight
1,000 horse-power	15 metric tons
2,000 horse-power	25 metric tons
3,000 horse-power	34 metric tons
4,000 horse-power	42 metric tons
5,000 horse-power	50 metric tons

218. Weights per horse-power. A ¼-h.p. 1,200-r.p.m. polyphase induction motor weighs a matter of 19 lb. while a 10,000-h.p. 120-r.p.m. polyphase induction motor would weigh some 176,000 lb. It is interesting to note that while the large motor has 150,000 times the output of the smaller, it only weighs about 9,000 times as much. Moreover its speed is about one-tenth as great as that of the smaller motor.

219. Starting apparatus for standard polyphase induction motors. Ninety per cent. of all the induction motors built in America are of the squirrel-cage type. Whereas the squirrel-cage motor when of small size is switched directly on the line at starting, it is necessary in starting larger squirrel-cage motors to employ induction starters or else the star-delta method. Slip-ring induction motors are started by means of a rheostat connected into the rotor circuits, and gradually cut out as the motor acquires speed. With the growth of electricity-distributing net-works, it has become expedient to relax the earlier onerous requirements imposed in the matter of permissible starting currents. On some systems fairly large squirrel-cage motors are permitted to be started by switching directly upon the line without induction starters. Designs in which the "deep-slot" effect (Par. 190) is correctly employed may be started directly from the line with a more moderate rush of current, and hence are the more appropriate as regards the lesser line disturbance at starting.

220. Induction-motor starting currents. The currents taken by good three-phase squirrel-cage induction motors at the moment of starting have values approximately in accordance with the following table, which corresponds to $q_x = 0.13$ and $s = q_{r_2} = 0.04$, see Figs. 91 and 92 and accompanying text.

A	*B*	*C*	*D*
Pressure at motor in per cent. of line pressure	Line starting current in per cent. of full-load current	Motor starting current in per cent. of full-load current	Starting torque of motor in per cent. of its full-load running torque
40	112	280	32
60	250	420	72
80	450	560	128
100	700	700	200

221. Calculated starting characteristics. The following table, from page 451 of the 2nd Edition of Hobart's "Electric Motors" (Whittaker & Co., London, 1910) gives the calculated starting characteristics of a 6-pole 25-cycle 200-h.p. 500-rev. per min., squirrel-cage, three-phase, induction motor.

The motor to which these last results correspond, was designed for very high efficiency and without any regard to starting torque ($q_s = 0.12$ and $s = 0.02$). Consequently, we find that when started on the six-tenth taps of the induction starter, the starting torque is only 55 per cent. of full-load running torque and the line current is practically three times full-load current, a worse result than that of the average motor corresponding to the earlier table. By employing the "deep-slot" principle in the design of 60-cycle squirrel-cage induction motors, the application of the full-line pressure to starting will be accompanied by a much smaller flow of current from the line than that shown in the table for the average motor. While the torque ma

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also be smaller, it will nevertheless be as great as the torque corresponding to the tap on the induction starter, which corresponds (in the average motor) the lower line current. Thus nothing is sacrificed except that the motor's power-factor will be a few per cent. lower at full-load and the customer is spared the outlay for an induction starter. Further, the operation of starting is reduced to elemental simplicity.

Pressure at motor terminals in per cent. of normal pressure	Motor's starting current in per cent. of full-load current	Line starting current in per cent. of full-load current	Input to stator (watts)	Stator copper loss (watts)	Input to rotor (watts)	Starting torque (meter kilograms)	Starting torque in per cent. of full-load running torque
33	274	91	56,600	33,300	23,300	44.3	15.1
40	330	132	86,000	48,000	38,000	72.3	24.3
60	495	297	194,000	108,000	86,000	164.0	55.0
80	660	528	344,000	192,000	152,000	289.0	97.0
100	824	824	540,000	299,000	241,000	455.0	153.0

221(a). Characteristics of very-low-periodicity induction motors. It is often desirable to have certain pieces of apparatus run at a slow speed, say from 80 to 200 r.p.m. Sixty-cycle induction motors of medium output, say 500 horse power, and for such slow speeds, would have many poles and large diameters and poor characteristics with respect to magnetizing current and stalling load. The power factor of such motors would be low at full load, say from 0.60 to 0.75. From quarter to half load, the power-factor would be far worse, say 0.4 to 0.5. Using a low frequency induction motor, for example some 8 to 10 cycles, one obtains a small number of poles, a power-factor at full load which will be of the order of 0.95 and which will still be some 0.90 at quarter load. The full-load efficiency of such a motor is from 2 per cent. to 3 per cent. higher than that of the 60-cycle motor, and is also very high (some 0.90 per cent.) at quarter to half load. Hence the apparent efficiency of such a low-frequency 500-hp. motor is a matter of 90 per cent. as against not over 70 per cent. for a 60-cycle motor. This permits of important savings in the line, transformers and generating equipment.

221(b). Characteristic and applicability of very-high-frequency induction motors. For applications where many small and very-high-speed motors are required, a frequency-changer set is employed by the General Electric Co. to obtain the necessary frequency transformation. These frequency changers are wound to give 225 volts at 120 cycles, in one series, and 115 volts at 200 cycles in the second. However, in the first series the frequency changers can be run at speeds to give from 100 to 199 cycles and in the second series from 200 to 300 cycles. The high-frequency motors are designed to operate throughout the range of frequency in the series for which they are wound. They are all bipolar. In the first series, synchronous speeds from 6,000 to 12,000 r.p.m. are obtained, and in the second series, from 12,000 to 18,000 r.p.m. Weights and other data are given in the following Table:

Arbitrary designating letter	H.p. at 7,200 r.p.m. and 220 volts	H.p. at 12,000 r.p.m. and 110 volts	Weight of stator and rotor complete in lb.	Approximate overall diameter in inches	Approximate length over end windings in inches
A	0.30	0.33	4½	3 41/64	3½
B	0.75	1.0	7¾	4 45/64	4½
C	1.25	1.5	10½	4 53/64	5½
D	1.5	2.5	18½	5 45/64	6½
E	3.0	5.0	27½	5 53/64	7¾

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Thousands of these motors are in use at these frequencies, for such purpose as the grinding of small bearings, especially ball races, where, in order t secure a satisfactory cutting speed, speeds up to 18,000 r.p.m. have been used also oil separators of the centrifugal type, for which, in some cases, speed up to 16,200 r.p.m. have been used. They are also used for driving woo shapers and wood carving machinery, where, in order to get a reasonabl cutting speed, high rotative speeds are necessary. The manufacturer of th special apparatus usually mounts the motors directly on the shaft or spindl of the machine to be driven and provides, at the same time, the outsid casing to support the stator.

INDUCTION GENERATOR

222. Theory of operation. If a polyphase induction motor, whil running light, and still connected to its supply circuit, be mechanicall driven above synchronism, the slip will be negative, the secondary con ductors will cut the revolving flux in the opposite direction, the secondar e.m.f. and current will reverse with respect to the flux, and the torque rea tion of the secondary current will oppose the rotation. This means mecha ical power absorbed and a reversal of the direction of power flow across th air gap, i.e., generator action. A little consideration will show that th torque characteristic above synchronism will be approximately symmetric with that below synchronism, referred to the point of synchronism, as Fig. 111.

Induction generators are dependent for their excitation upon laggin current drawn from synchronous generators, or leading current delivere to synchronous motors connected to the network into which the inductio generators deliver their output. Therefore the induction type of generat requires no separate exciter for the purpose of supplying continuous curre to its field windings, and is consequently much simpler in its electrical con struction than the synchronous type.

However the induction generator is subject to the very definite limitatio that it is operative only when connected in parallel with a synchronou generator, or in parallel with a supply network to which there is at least on synchronous generator connected, as otherwise it would be cut off from it source of exciting current.

223. Circle diagram of induction generator. The characteristics the induction generator can be most easily determined from the circle dia gram. For this purpose we may still use the induction-motor approximat equivalent circuit scheme of Fig. 103 with the understanding that s is negati which means an *apparent* negative reactance sx_2, and an *apparent* negati resistance $(r_2/s)(1-s)$. This means that the power delivered to this resi ance is negative, and simply an electrical equivalent of the source of m chanical driving power. Upon this basis, it is evident that the locus of th extremity of I_1 is a circle for the induction generator as well as for the indu tion motor, as there is no abrupt change in the vector diagram when s pass through zero.

224. Interpretation of circle diagram. The approximate circle diagra of the induction generator is given in Fig. 110, where the notation correspon to that of Fig. 104 for the induction motor. The principal characteristics d rived from the circle diagram are shown in Fig. 111. Referring to Fig. 110, $\overline{F}$ represents the total power delivered to the generator (shaft-friction, win age, and rotor-core loss excluded); $\overline{FG}$ represents the rotor copper loss, $\overline{G}$ the total power transmitted across the air gap to the stator; $\overline{GH}$ the stat copper loss; $\overline{HK}$ the stator-core loss; and $\overline{KB}$ the output $E_2 I_1 \cos \theta_2$. Th slip is $s = FG/GB$.

225. Power-factor and excitation. Thus the induction machi driven above synchronism, pumps power back into the line, the amou depending upon the slip. But the power-factor of the output is fixed, n by the nature of the load but by the slip and the constants of the machi itself. The induction machine always carries a quadrature current wh operating either as motor or as generator. It may be said to receive a qua rature lagging current, or to deliver a quadrature leading current. Th quadrature current is the excitation of the machine, a part I_m for the ma flux, and the remainder (or its equivalent in quadrature volt amperes) f

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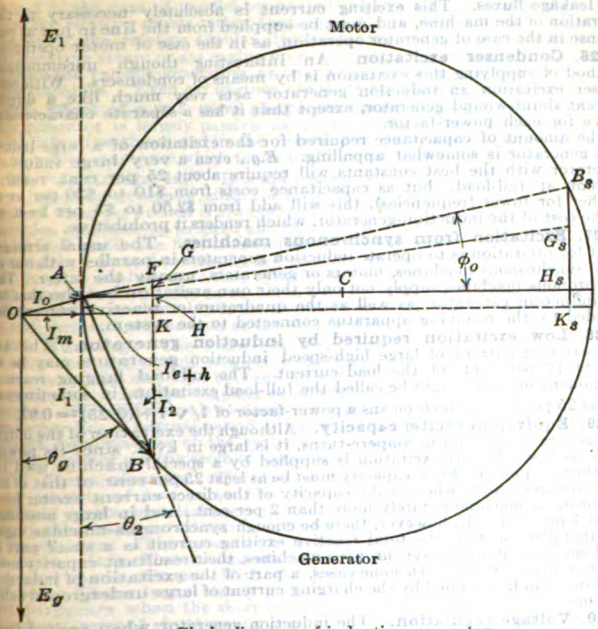


FIG. 110.—Circle diagram of induction generator.

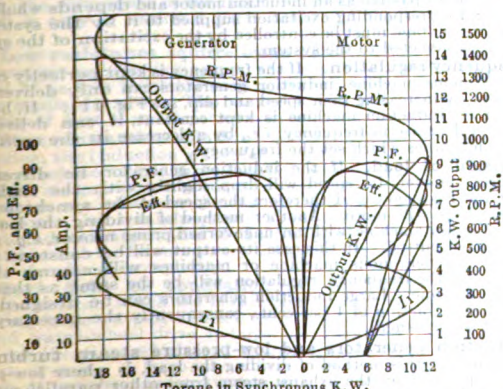


FIG. 111.—Generator and motor characteristics of induction machine.

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the leakage fluxes. This exciting current is absolutely necessary to the operation of the machine, and must be supplied from the line in just as real a sense in the case of generator operation, as in the case of motor operation.

226. Condenser excitation. An interesting though uncommercial method of supplying this excitation is by means of condensers. With condenser excitation an induction generator acts very much like a direct-current shunt-wound generator, except that it has a separate characteristic curve for each power-factor.

The amount of capacitance required for the excitation of a large induction generator is somewhat appalling. *E.g.*, even a very large induction generator with the best constants will require about 25 per cent. reactive current at full-load; but as capacitance costs from $10 to $20 per kv-a. (higher for lower frequencies), this will add from $2.50 to $5 per kv-a. to to the cost of the induction-generator, which renders it prohibitive.

227. Excitation from synchronous machines. The usual arrangement for excitation is to operate induction generators in parallel with one or more synchronous machines, motors or generators, usually the latter. The synchronous machines supply not only their own excitation but also that for the induction generator, as well as the quadrature or reactive current demanded by the receiving apparatus connected to the system.

228. Low excitation required by induction generator. The no-load exciting current of large high-speed induction generators may be as low as 12 per cent. of the load current. The full-load lagging reactive component or what might be called the full-load excitation, is sometimes as low as 25 per cent., which means a power-factor of $1/\sqrt{1+(0.25)^2}=0.97$.

229. Equivalent exciter capacity. Although the excitation of the induction generator is small in ampere-turns, it is large in kv-a. since its power-factor is low. If this excitation is supplied by a special machine used for no other purpose, its kv-a. capacity must be at least 25 per cent. of that of the induction generator, whereas the capacity of the direct-current exciter for a synchronous machine is rarely more than 2 per cent., and in large machines about 1 per cent. If, however, there be enough synchronous-machine capacity installed, so that the total reactive exciting current is a small part of the load current of the synchronous machines, their resultant capacity need not be much increased. In some cases, a part of the excitation of induction machines can be supplied by the charging current of large underground cable systems.

230. Voltage regulation. The induction generator when excited from synchronous machines has no inherent regulation as to voltage, since in this respect it is quite as passive as an induction motor and depends wholly upon the voltage and corresponding excitation supplied to it by the system. In other words, the voltage must be controlled by the excitation of the synchronous machines connected to the system.

231. Frequency regulation. If the frequency is kept perfectly constant by the synchronous machine, induction generators can only deliver an increased output by increasing their speed and slip, see Fig. 111. If, however, the speed of an induction machine is kept constant, it can deliver more load only by a decrease in frequency, *i.e.*, by a decrease in the speed of the synchronous machines which set the frequency.

232. Division of load. If the induction generator be driven by a governed prime mover, its speed will drop slightly with the load, which means that the frequency and therefore the speed of the synchronous machines must drop still more. Another method of dividing the load is to drive the induction machine with an ungoverned prime mover, *e.g.*, a steam engine with fixed cut-off. In this case its output will be constant, and the speed-governed synchronous machine or machines will assume the load fluctuations, and the frequency regulation will be the same as that of the synchronous machine. Large induction generators can be designed with a full-load slip of a fraction of 1 per cent., consequently the necessary variation of speed is very small.

233. Induction generators and low-pressure steam turbines. A very good place for this method of dividing the load, is where low-pressure turbines are operated by the exhaust steam from other parallel-connected steam units. The exhaust turbines can be operated without governors thus utilising all the exhaust steam, and yielding the highest economy.

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234. Effect of angular variation of prime movers. Since the division of load in the case of parallel-connected induction generators is dependent upon the relative speeds rather than upon the relative angular positions of the rotors, the relative angular displacements within one revolution of a reciprocating steam or gas engine do not produce objectionable power surges between the various generators, as frequently occurs in the case of synchronous machines. Even gas engines are quite satisfactory in this connection.

235. Effect of e.m.f. wave shape on parallel operation. The induction generator is largely passive as to wave shape, the latter being impressed from without, and in the presence of e.m.f. harmonics, behaves like an inductive reactance which tends to damp the harmonic currents.

236. "Switching in." It is not necessary to synchronize when throwing in an induction generator, since the latter has no e.m.f. until excited from the line and when so excited is always in phase. It is only necessary to get the induction machine up to speed and throw it in. As the machine cannot pick up its load until the field is established, the first rush of current is wholly exciting current and practically independent of the slip. This initial current rush is quite analogous to that experienced when switching in transformers, and is explained on the same basis. Since with large units this exciting current rush is undesirably large, reactance coils are inserted while switching in, and then cut out as soon as the steady state is reached.

237. Hunting. The connection between the speed of a synchronous machine and its circuit frequency is exactly analogous to a mechanical elastic coupling, and that between an induction machine and its impressed frequency, to a friction coupling in which the friction grip is proportional to the slip. The latter tends to damp out any oscillations of the system, while the former has a natural period of its own which may tend to amplify some periodic disturbances of the system. The induction machine is thus decidedly superior on the score of hunting.

238. Short-circuits. The short-circuit current of a synchronous alternator consists of two parts: first, the transient part limited only by the combined equivalent leakage reactance of armature and field circuits; and second, the steady part determined by the much larger synchronous reactance of the armature. The former is the serious element, from three to five times the latter. It is this transient effect that twists the armature coil ends as if they were made of rope. With the induction generator the case is quite different. There is no steady portion, since the source of exciting current disappears when the short-circuit occurs, just exactly as in the case of a direct-current shunt-wound generator. The transient effect is present, but in only small degree since, with the same flux as in the synchronous machine, the reluctance of the magnetic circuit (and hence the energy of the field) is only a fractional part (sometimes less than 10 per cent.) as great.

239. Low resistance squirrel-cage rotor. Since the induction generator requires no starting torque, the rotor is always of the squirrel-cage type and of as low resistance as is consistent with the cost of the copper and the available space. This means a very low secondary-copper loss, and a slip of less than 0.5 per cent. in large machines.

240. First cost and ventilation. Owing to the exceedingly simple rotor construction, the induction generator would be cheaper to build than a synchronous machine of the same capacity, were it not that the short radial depth of the air gap makes ventilation very difficult, and the more so in those ratings which are otherwise the best suited to this type of machine. This, together with the tooth-frequency losses incident to the short air gap, makes the induction generator of doubtful superiority except in special cases. The switchboard is, however, very much simpler, and the switching operations are of reduced complexity.

241. Best field of application for induction generators. The specifications from which the best induction machines can be produced are high speed, large output, and low frequency, which means steam-turbine or high-head water-wheel drive in large power stations. Unfortunately these are the specifications which lead to great difficulties in ventilation, owing to the short air-gap. A large city-railway system with the load considerably made up of synchronous converters with underground-cable distribution, satisfies the conditions as to excitation.

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THE DESIGN OF INDUCTION MACHINES

243. Specifications. For an induction machine the principal specifications are as follows: frequency; number of phases; speed; terminal voltage; rated output; nature of duty, continuous or intermittent service; maximum allowable temperature rise; insulation tests; stalling torque; starting torque; starting current; and, sometimes, speed regulation; power-factor; and efficiency. See also Sec. 24.

244. Symbols.

A = tooth-tip constant for tooth-tip leakage calculation
a_1 and a_2 = primary and secondary slot contraction factors
$\mathfrak{B}$ = crest value of air-gap flux density (lines per sq. in.)
$\mathfrak{B}_t$ = maximum flux density in narrow part of tooth (lines per sq. in.)
C = constant in Kierstead's formula for leakage factor
C'' = copper section (sq. in.) per in. of periphery
D = air-gap diameter (in.)
d_s = slot depth (in.)
E'_1 = induced voltage per phase
e'' = volts induced per in. of active primary conductor
f = frequency (cycles per sec.)
h_c = copper loss per sq. in. of gap surface (watts)
K = Total kw. developed = $P'_1 + 1{,}000$
$K_1 = a_1 a_2$ = combined slot contraction factor
K_2 = ratio of air-gap amp-turns to total amp-turns
K_d = duct contraction factor
$Kf = k_f \varphi_f$, Fig. 101
k = ratio pole pitch to core length
k_B = belt reactance factor, Fig. 102
k_b = belt differential factor, Par. 31
k_f = length of coil end ÷ pole pitch
k_o = h.p. output per sq. in. of projected area of air-gap cylinder
k_p = pitch differential factor, Fig. 22
k_s = slot-reactance constant
k_w = slot space-factor
l = gross length of core
N_{cpp} = conductors per pole per phase
N_i = ampere-turns
N_{sp} = No. of slots per pole (average of primary and secondary)
N_{spp} = slots per pole per phase
P'_1 = Power transmitted across air-gap
p = No. of pairs of poles
p' = No. of phases
q = total quadrature component ($= q_m + q_s$)

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q_{il} = net iron length ÷ gross core length
q_m = ratio of exciting current to torque current
q_p = ratio of coil pitch to pole pitch
q_r = resistance drop ÷ induced volts
q_{so} = slot opening divided by tooth pitch
q_{sw} = slot width ÷ tooth pitch
q_x = leakage reactance volts ÷ induced volts
q_{xB} = belt-leakage reactance volts ÷ induced volts
q_{xf} = coil-end reactance volts ÷ induced volts
q_{xs} = slot reactance volts ÷ induced volts
q_{xt} = tooth-tip leakage reactance volts ÷ induced volts
R = rev. per min.
S = slot factor
s = slip
$t.w.c.$ = total works cost (dollars)
V_{cu} = total volume primary copper (circular-mil in.)
v = peripheral velocity at synchronism (ft. per sec.)
w_s = width of slot (in.)
Δ = torque-current amp. conductors per in. of periphery
Δ_1 = primary amp. conductors per in. of periphery
Δ_m = magnetising current amp. conductors per in. of periphery
δ = radial depth of air-gap (in.)
ξ = output coefficient, h.p.
ξ_k = output coefficient, kw.
σ = leakage factor (sometimes also termed the circle ratio and sometimes the dispersion coefficient)
τ = pole pitch (in.)
τ_t = tooth-pitch (in.)
φ_f = flux per amp. in. of phase belt bundle of coil-ends, Fig. 100

Subscript 1 refers to primary.
Subscript 2 refers to secondary.

245. The output equation. The volt-amperes induced per sq. in. of peripheral surface are, $\Delta e'' = 8.5 k_1 k_p v B \Delta 10^{-8}$, see Par. **23**. and the total kw. developed are

$$K = 8.5 \times \pi k_1 k_p \Delta v B D l 10^{-11} \quad \text{(kw.)} \qquad (71)$$

This is the power P'_1 transmitted across the air gap and not the output, which is less by the secondary copper loss and the friction and windage loss. Assuming the latter to be about 1 per cent. and remembering that $q_{r_2} = s$, we get as the horse-power output

$$\text{h.p.} = 3.55\ (1-s)\ k_1 k_p \Delta \mathfrak{B} v D l 10^{-10} = k_o D l \qquad (72)$$

where

$$k_o = 3.55\ (1-s) k_1 k_p \Delta \mathfrak{B} v 10^{-10} \qquad (73)$$

is the **specific output** in horse-power per sq. in. of projected area of the air-gap cylinder. Assuming a three-phase motor ($k_1 = 0.95$), of moderate capacity, with squirrel-cage rotor ($s = 0.03$), and five-sixths pitch of coils ($k_p = 0.96$),

$$k_o = 3.2 \Delta \mathfrak{B} v 10^{-10} \qquad (74)$$

By substituting for v in equation 72, its value ($\pi DR/720$), we get

$$\text{h.p.} = 1.55\ (1-s) k_1 k_p \Delta\ \mathfrak{B} D^2 l R 10^{-12} = \xi D^2 l R \qquad (75)$$

where ξ is called **output coefficient.** With the same assumptions as above,

$$\xi = 1.38 \Delta \mathfrak{B} 10^{-12} \qquad (76)$$

If horse-power be replaced by kilowatts in Eq. 75,

$$\xi_k = 1.03 \Delta \mathfrak{B} 10^{-12} \qquad (77)$$

Sometimes the output equation is more convenient in the form of Eq. 72, and sometimes in that of Eq. 75. Referring to Eqs. 72 and 75, and assuming R specified, $\mathfrak{B}$, Δ, and v determine Dl, and $D = (720v)/(\pi R)$; or $\mathfrak{B}$ and Δ determine $D^2 l$, and $k_2 = \tau/l = (\pi D)/(2pl)$, determines the ratio of D to l. As the cost of the machine increases approximately with Dl and with $D^2 l$, $\Delta\mathfrak{B}$ should be as large as possible.

246. Representative values of output coefficient. ("Design of Polyphase Generators and Motors," Hobart.)

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Pole pitch in.	Values of output coefficient, Σ, when output is expressed in horsepower, linear dimensions in in., and speed in rev. per min.					
	4 pole	8 pole	12 pole	16 pole	20 pole	24 pole
5	.....	2.5×10^{-5}	2.65×10^{-5}	2.63×10^{-5}	2.54×10^{-5}	2.46×10^{-5}
7	2.22×10^{-5}	3.29	3.31	3.31	3.31	3.31
10	3.36	3.9	3.94	3.94	3.94	3.94
12	3.92	4.36	4.38	4.40	4.43	4.43
16	4.34	4.82	4.84	4.86	.....	.....
20	4.54	5.05	.....	.....	.....	.....

247. Considerations affecting choice of $\mathfrak{B}$, v, and Δ. A few of the most important are given below in Par's. **248** to **256**.

248. Tooth density limit (Par. 247). See Par. **95**. The upper limit of $\mathfrak{B}_t$ is lower than for alternators because of tooth-frequency losses. $\mathfrak{B}_t$ = 85,000 to 105,000, the higher values for nearly closed slots. With open slots it is not always possible to utilize the tooth section to its limit, because of the low gap density $\mathfrak{B}$, Par. **249**.

249. Stalling torque and power-factor (Par. 247). The value of $\Delta/\mathfrak{B}$ must be kept below the point at which q_x exceeds a value which is safe from the standpoint of stalling torque (Eq. 53 and 62a). On the other hand, a small value of $\Delta/\mathfrak{B}$ means a large exciting current and low power-factor. (Eqs. 58 and 52.) On this account $\mathfrak{B}$ must be much smaller than for alternators, except in the case of large high-speed motors (large τ). The ratio $\Delta \div \mathfrak{B}$ is thus an important one.

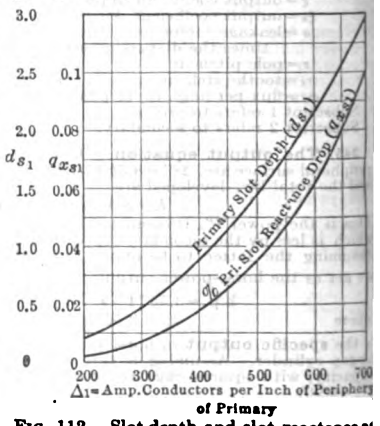


FIG. 112.—Slot depth and slot reactance as a function of the peripheral loading for a normal 5-h.p., 60-cycle open-(stator)-slot motor $h_c = \Delta \div m$ assumed constant.

250. Heating (Par. 247). Same as for Alternators (Par. 96) except that the inherent ventilation is less good because of the short air-gap.

For well-ventilated open motors a rough preliminary guide is

$$h_c = 0.4(1+0.012v) \quad (78)$$

Although the slot depth increases as Δ^2 (h_c constant), it would be possible to increase Δ, d_s and $\mathfrak{B}$ considerably beyond present limits without change of $\Delta/\mathfrak{B}$ (Par. **249**) were it not for the slot reactance, Par. **251**.

251. Slot reactance (Par. 247). It can be easily shown (Eq. 62a and Par **250**) that the per cent. slot reactance volts (q_{x_s}) is, for constant h_c, proportional to Δ^2, see Fig. 112. This places the upper limit on d_s, Δ and therefore on $\mathfrak{B}$, since $\Delta/\mathfrak{B}$ is critical, Par. **249**. Approximate values of Δ and d_s for open (stator) slot motors are shown in Fig. 113.

252. Limits of peripheral velocity. v has two principal upper limits (a) the cost and weight of copper (Par. **253**), and (b) the reactance (Par. **256**) but in this case it is the coil-end reactance in place of the slot reactance.

253. Copper limitation of peripheral velocity (Par. 252). As in the case of the alternator (Par. **103**) the value of k_3 for minimum copper is

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sumed constant in determining the above value of k_3, will flatten the minimum still more and raise the desirable values of v and k_3. Fig. 115 shows for a series of 100-h.p., 25-cycle, three-phase, squirrel-cage motors at various speeds, the influence which k_3 exerts on the cost, and Fig. 116 shows the corresponding values of the circle ratio.

It is instructive also to regard the cost from another standpoint. The cost of the copper and laminations is first estimated, and is designated as the cost of net effective material. If we designate the overall diameter [in inches] by D_o and the gross core length [in inches] by l, we may take the cost of the labor, the overhead charges and the structural material, in dollars, as $(D_o^2/11) + 0.20 D_o l$. It is seen from this formula that a motor with an overall diameter of 80 in. will have an overhead cost approaching $(\overline{80}^2/11) = \$580$, as l approaches zero. If l is equal to 16 in., the cost to be debited to labor, overhead charges and structural material amounts to $(580 + 0.20 \times 80 \times 16) = \$836$. The total works cost is \$836 plus the outlay for the net effective material. While such methods require adjustment to the varying conditions in different works, it is nevertheless instructive to employ them. The above investigation is based on pre-war data. Costs of labor and material are still too unsettled to justify establishing equivalent formulæ for future use.

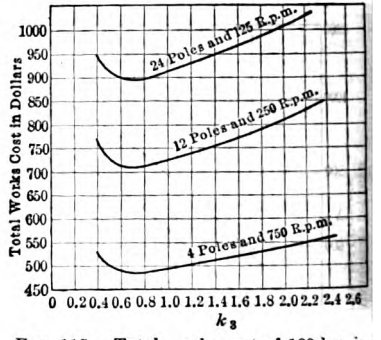


FIG. 115.—Total works cost of 100-h.p. induction motors as function of ratio pole-pitch to gross core length. Full-pitch winding assumed.

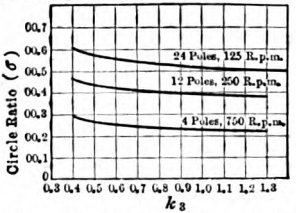


FIG. 116.—Circle ratio of induction motors as a function of ratio of pole pitch to gross core length.

From the relation $k_3 = 0.71/q_p$ for minimum total works cost, it can be shown that:

$$\tau = \frac{0.79}{q_p}\sqrt[3]{\frac{KR}{\xi f^2}} = \frac{780}{q_p}\sqrt[3]{\frac{KR}{\Delta \mathfrak{B} f^2}} \quad (80)$$

Average values employed for τ are shown in Par. **255.**

255. Pole pitch (in.) for three-phase squirrel-cage motors

Frequency	Rated output h.p.	4 poles	6 poles	8 poles	12 poles	16 poles	24 poles
25 Cycles	10	7.5	6.3	5.5	.....	.....	.....
	20	8.7	7.5	6.7	5.5	.....	.....
	40	10.2	8.7	7.9	6.8	.....	.....
	80	11.8	10.2	9.5	8.3	.....	.....
	150	13.8	11.8	10.6	9.5	.....	.....
	400	18.5	15.8	14.2	12.2	.....	.....
60 Cycles	10	6.7	5.5	4.7	.....	.....	.....
	20	7.5	6.3	5.5	4.7	.....	.....
	40	8.7	7.5	6.7	5.5	5.1	.....
	80	9.7	8.5	7.9	6.7	6.3	5.5
	150	11.0	9.4	8.7	7.9	7.1	6.3
	400	14.0	12.2	10.8	9.5	8.5	7.5

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256. Coil-end-leakage limit of peripheral velocity. The other limit to v is the coil-end leakage, which is proportional to v^3 (see Par. **196**, Eq. 62a, and remember that k_3 is proportional to v^3). q_{zf} has been computed for the 10-h.p. motor of Fig. 114, and is plotted in Fig. 117. If Δ were taken larger, both the total copper and the q_{zf} curves of Fig. 114 would be higher. A change in $\mathfrak{B}$ would not affect either appreciably. By using a fractional-pitch winding, both of these curves would be lowered somewhat, but there is a limit to this, owing to the necessity for more active conductors to generate the same e.m.f., or larger values of $\mathfrak{B}$ and q_m. A larger value for R would lower both, and a larger h.p. would lower q_{zf}; but these are specifications. The curves of Fig. 117 show without necessary comment why v may not be carried above a pretty definite upper limit for any given specifications.

257. Fractional-pitch windings. The use of any considerable pitch reduction or chording (beyond the five-sixths used for the curves of Figs. 118 to 121) means an increased exciting current (q_m) and a decreased reactance (q_z), other things being equal. If the motor in question were properly designed for full pitch, the pitch reduction should be accompanied by a decrease of $\mathfrak{B}$, an increase of Δ and of v. This will not usually increase either the power-factor or the specific output (k_o or ξ), but rather the reverse. It will, however, increase the diameter and decrease the length of the core, thus increasing the natural heat-dissipating power of the machine. It will also reduce the overall length, which in some cases means a considerable saving in cost. The most obvious place for the fractional-pitch winding is the two-pole motor, where a pitch as low as 0.5 is sometimes used.

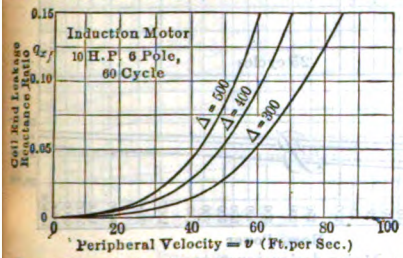


FIG. 117.—Coil-end leakage as function of peripheral velocity and of peripheral loading for a 10-h.p. motor.

258. Data. Figs. 118 to 121 give values of $\mathfrak{B}$, v and Δ_1, and the corresponding values of q_z, q_m, q, k_o, ξ, k_3, and power-factor, for three-phase squirrel-cage motors with open-stator slots and nearly closed-rotor slots, and a coil pitch of five-sixths except where otherwise designated. The curves have been computed on the following basis; Δ_1 is approximated largely on the basis of heating; the values of $\mathfrak{B}$ are a compromise between first cost and stalling torque on the one hand and power-factor on the other, with more weight given to the former; k_3 (upon which v depends) is a compromise between cost and ventilation. From these assumed values the other quantities have been computed. Both $\mathfrak{B}$ and k_3 are larger than are frequently met with in practice, and doubtless too large to meet some specifications.

If closed slots had been used on the stators, larger values of $\mathfrak{B}$ could have been employed to advantage, not only because of the lower reluctance of air-gap but also because of the higher allowable tooth density. This increased $\mathfrak{B}$ does not ordinarily result in an increase of power-factor, sometimes the reverse is true; but it does mean a smaller machine and less active material. This may or may not mean a cheaper machine, according as the extra cost of labor in winding is or is not made up by the saving in material. In general it would be cheaper in Europe and more expensive in this country.

Two-pole motors are rarely met with and the data for this type is given to show possibilities and the value of low coil pitch for two poles. The disadvantage is chiefly connected with the poorer natural ventilation of a long-core machine with short air-gap.

259. Caution. Such information as given in Figs. 118 to 121, and elsewhere in tables or curves, should be taken only as a rough guide, and as indicating the relations between the several quantities involved, rather than their absolute values. These latter may be altered over a moderate range to suit special specifications, and will vary considerably in machines designed by different engineers to meet the same specifications. Some engineers use practically the same value of $\mathfrak{B}$ in all sizes for a given frequency.

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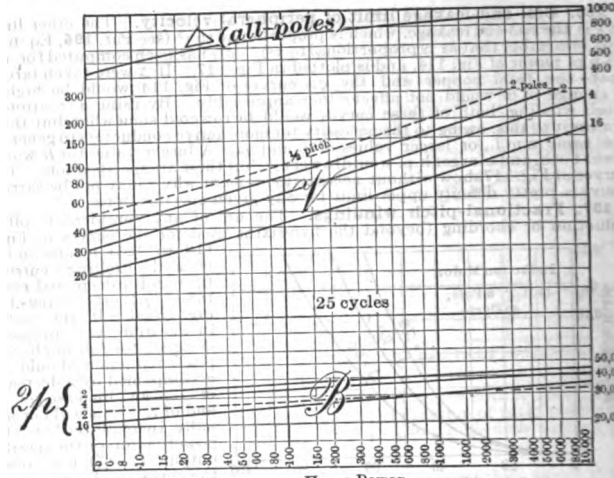


FIG. 118.—Major design constants.

$2p$	2	2	4	16
q_p	½	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$
k_3	2.0	1.8	1.6	1.3

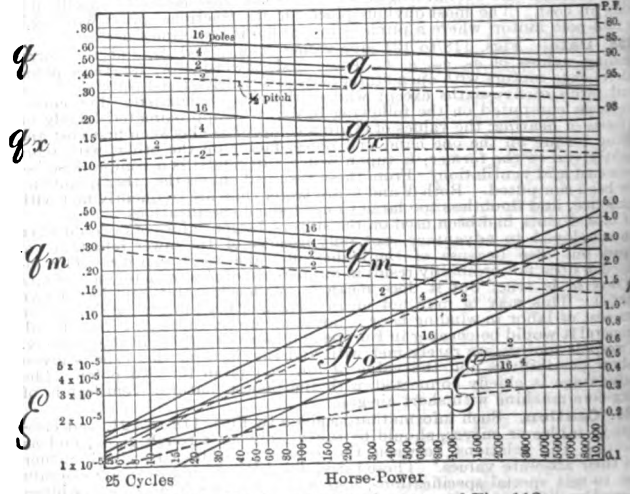


FIG. 119.—Vital constants of motors of Fig. 118.

FIGS. 118 AND 119.—25-cycle 3-phase squirrel-cage induction moto
Stator slots open. Rotor slots nearly closed.

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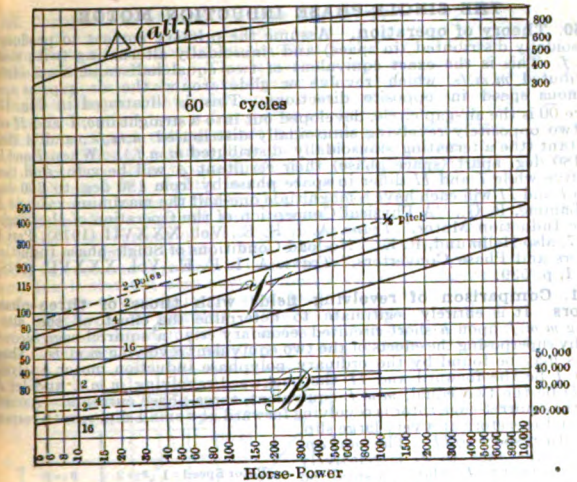


FIG. 120.—Major design constants.

$2p$	2	2	4	16
q_p	$\frac{1}{2}$	$\frac{8}{9}$	$\frac{8}{9}$	$\frac{8}{9}$
k_3	2.0	1.8	1.6	1.3

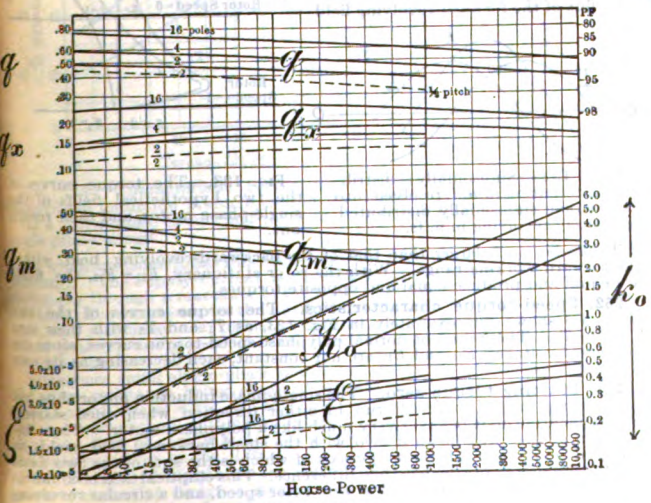


FIG. 121.

FIGS. 120 AND 121.—60-cycle 3-phase squirrel-cage induction motors. Stator slots open. Rotor slots nearly closed.

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THE SINGLE-PHASE INDUCTION MOTOR

260. Theory of operation. Assume the primary current to produce a sinusoidally distributed (in space) and sinusoidally alternating (with time) *m.m.f.* This is the exact equivalent of two equal half-value sinusoidally distributed *m.m.fs.* which revolve or glide around the air gap at synchronous speed in opposite directions. This is illustrated in Fig. 122 where $\bar{0}\bar{0}$ is the air-gap circle, developed out into a straight line, *I* and *II* are the two oppositely revolving sinusoidally distributed *m.m.fs.*, and *A* their resultant (the alternating sinusoidally distributed *m.m.f.*). When *I* and *II* are 180 deg. apart (space phase) their resultant *A* will be zero, and then negative while *I* and *II* differ in space phase by from 180 deg. to 360 deg. Thus *I* and *II* will each have a magnitude one-half the maximum value of *A*. See Lamme, B. G., "A Physical Conception of the Operation of the Single-phase Induction Motor," *Trans.* A. I. E. E., Vol. XXXVII (1918), Part I, p. 627; also Hellmund, R. E., "No-load Conditions of Single-phase Induction Motors and Phase Converters," *Trans.* A. I. E. E., Vol. XXXVII (1918), Part I, p. 539.

261. Comparison of revolving fields with those of three-phase motors. It is entirely legitimate to determine the effect of the alternating *m.m.f.* upon a short-circuited secondary (*e.g.*, a squirrel-cage secondary) by superposing the effects of the two equivalent revolving *m.m.fs.* These effects may be found by the ordinary polyphase induction motor analysis.

Let *I* be the forward and *II* the backward-revolving *m.m.f.* and let J_1 and J_2 be the two equal, *m.m.f.*-equivalent, three-phase currents. Assume that the squirrel-cage rotor is revolving forward at a small slip, *s*, with respect to *I*, and therefore at a very large slip, $2-s$, with respect to *II*. The *total apparent impedance* to J_1 is relatively large, and that to J_2 relatively small, so that the e.m.f. E_{11}, absorbed by J_1, will be large as compared to the e.m.f. E_{12} absorbed by J_2. The total impressed e.m.f. will be E_1, the vector sum of E_{11} and E_{12}. E_1 is assumed constant. The flux of the forward-revolving field will then be much larger than that of the backward-revolving field, within the forward working range. With the rotor stationary, $E_{11}=E_{12}$, the fields are equal and produce equal and opposite torques.

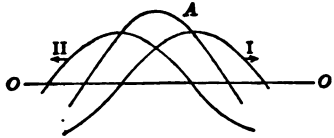


FIG. 122.—Sinusoidally distributed alternating m.m.f. resolved into two equal sinusoidally distributed oppositely revolving m.m.fs.

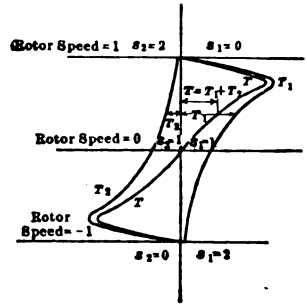


FIG. 123.—The torque curves of the two hypothetical fields of the single-phase motor, and their resultant.

262. Speed-torque characteristics. The torque curves of the two fields are shown approximately in Fig. 123, as T_1 and T_2 with their sum $T=T_1+T_2$. These are not normal polyphase speed-torque curves, since the impressed voltages E_{11} and E_{12} are not constant, each decreasing as its own slip increases.

263. Starting torque zero. The single-phase induction motor thus has no starting torque, but will run in either direction when once started. Near synchronism it behaves very much like a polyphase motor. The combination of the large forward field with the small backward field yields an elliptical revolving field, the major axis of which is the sum of the two fields and the minor axis of which is their difference. This elliptical field becomes an alternating or straight-line field at zero rotor speed, and a circular revolving field at synchronism.

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264. Comparison of single-phase and polyphase operation. A Y-connected three-phase motor with one terminal disconnected from the line will constitute a fairly normal single-phase motor, see Fig. 124.

265. Exciting current. This is nearly twice as large as for the three-phase case, approximately half of it being the reflection in the primary of the no-load secondary current which supplies an *m.m.f.* in space and time quadrature with the primary *m.m.f.* and thus produces a revolving field.

266. Output and rating relative to polyphase machine. The safe single-phase rating of a three-phase motor at rated voltage is about 60 per cent. of the three-phase rating at the same voltage, but a better balance of losses is obtained at a slightly increased line voltage, when the safe output may be increased to about two-thirds that of the polyphase case.

267. Secondary current and copper loss. Unlike the three-phase motor, the rotor current of the single-phase motor is not zero at synchronism, but has a definite value. This may be looked upon as a part of the exciting current, and is present in lesser degree at higher slips. The secondary copper loss is also not zero at synchronism and is no longer proportional to the slip. It is obviously larger at all loads than when running three-phase.

268. Methods of starting. The most common method of starting single-phase induction motors is known as the split-phase method. The motor is supplied with an auxiliary winding in space quadrature with the

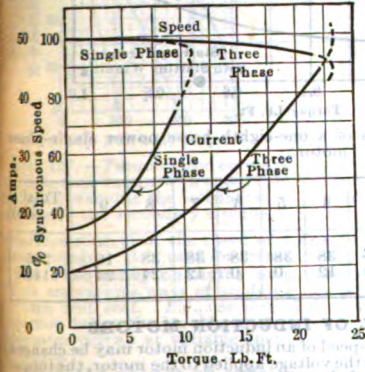


FIG. 124.—Characteristic curves of a three-phase induction motor operated (1) from a three-phase circuit and (2) from single-phase circuit.

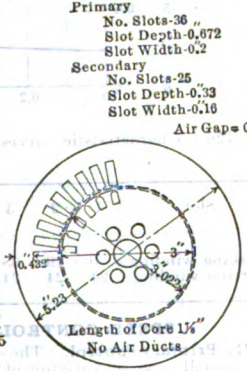


FIG. 125.—Dimensions and data of a one-eighth horse-power single-phase motor.

main windings (sometimes this consists of the third phase of a three-phase Y winding). The supply current is divided before it reaches the motor, one part going through a reactance to the main winding, and the other through a non-inductive resistance to the auxiliary or starting winding. If the resistance and reactance are properly chosen, the phase difference thus produced between the e.m.fs. E_m and E_a is sufficient to produce an elliptical revolving field.

Sometimes small single-phase motors can be thrown directly on the line, the extra resistance being obtained within the starting winding itself by using a small size of wire. In this case the cutting out of the starting winding is accomplished automatically by a centrifugal device. The dimensions and data of such a motor are given in Par. **270** and in Fig. 125. Its test data are given in Fig. 126.

269. Design of single-phase induction motor. From the above it is obvious that to design a single-phase motor means simply to design a good polyphase motor for about one and one-half times the desired single-phase output.

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270. Winding data for 0.125-h.p., 60-cycle, 4-pole, 110-volt, self-starting, single-phase induction motor. See Figs. 125 and 126. The main or working winding is wound with No. 20 wire and has 1,064 active conductors. The starting winding is wound with No. 25 wire and has 576 active conductors. For each winding the active conductors are connected in series. Numbering the slots for 1 pole from 1 to 9, the following table shows the distribution of the two windings.

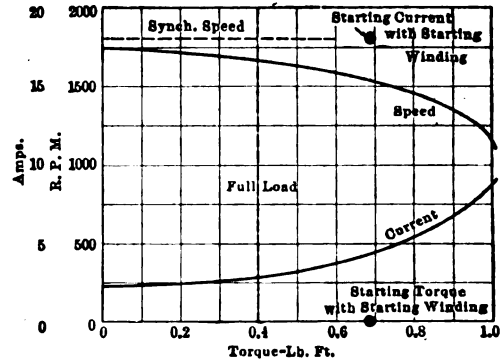


FIG. 126.—Characteristic curves of a one-eighth horse power single-phase motor.

Slot	1	2	3	4	5	6	7	8	9	Total (1 pole)
Working winding.	0	19	38	38	38	38	38	38	19	266
Starting winding.	24	24	24	12	0	0	12	24	24	144

SPEED CONTROL OF INDUCTION MOTORS

271. Primary control. The speed of an induction motor may be changed over a small range by variation of the voltage applied to the motor, the torque being proportional to the square of the voltage for any given slip. With a constant voltage supply, the voltage on the motor primary may be changed by using either series resistance or a compensator. Advantages of the primary system of control are the possibility of using the squirrel-cage rotor, and the simplicity of the resistance controller. A squirrel-cage rotor designed for this service is expensive, as its resistance must be high in order to obtain a reasonable speed variation. This results in large rotor losses, and therefore a large motor, so that the temperature may be maintained at reasonable values. Compensator control is complicated and expensive. Compensator coils cannot be short-circuited as can resistance, but must be cut out, and therefore a more complicated controller is necessary. Compensator control has a higher efficiency than resistance control, and takes less current; but it has a poorer power-factor.

272. Secondary speed control of induction motors. Speed variation can be obtained in an induction motor by using a wound rotor with slip-rings and connecting variable resistances between these slip-rings. By properly proportioning this rotor resistance, the starting current or the starting torque may be adjusted to any required value, and by properly designing the resistance steps, any speed-torque curve may be approximated. Fig. 127 gives four speed-torque curves where this type of control is used. Curve 1 is obtained with the slip-rings short-circuited and curves 2, 3, and 4 are

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obtained with increasing resistance steps. In Fig. 128 the current-torque curve for the above speed-torque curves, is shown, the torque per amp. being independent of the speed for this type of control. Since with this method speed variation is obtained by wasting energy in rheostats, it is not suited to continuous running at speeds much below synchronous speed.

273. Disadvantages of secondary-resistance control. For any one value of the resistance the speed changes greatly with variations of the load and rises to practically its synchronous value at no-load, whatever be the resistance. The higher the resistance, the more the speed will vary for a small change in load. An amount of power proportional to the speed reduction is lost in the resistance, that is, if the speed is decreased to 30 per cent. below normal, 30 per cent. of the energy taken from the line is lost.

274. Advantages of secondary-resistance control are simplicity of connections and relatively small increase in cost of motor, over that of a constant-speed induction motor. This method is exactly equivalent to the armature-series-

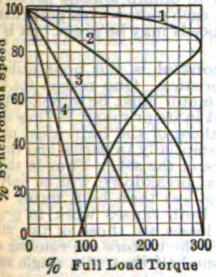


FIG. 127.—Torque speed curves of an induction motor with speed controlled by varying the resistances in series with the secondary circuits.

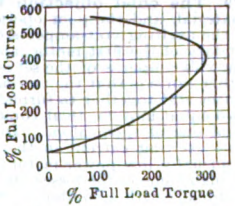


FIG. 128.—Torque-current curve for induction motor with secondary speed control.

resistance control of the speed of a direct-current shunt motor under constant voltage. It is used for cranes, elevators, rolling mills and mine hoists.

275. Frequency changing as a means of securing various speeds. There are various ways of applying this principle and all are characterized by high first cost. *E.g.*, use several alternators of different frequencies, an objection being the trouble in throwing over from one to the other; or use alternator driven at variable speed, when each motor must have its own alternator.

276. Speed change by variation of number of poles (multispeed motors). It is obviously possible by regrouping the coils on the stator of an induction motor so as to alter the number of poles, to also alter the synchronous speed of the motor. With pole-changing a squirrel-cage rotor is generally used, as with a wound rotor the rotor conductors must also be regrouped. But in certain services such as in rolling mills, secondary resistance control demands a wound rotor. With an ordinary two-layer drum winding the pitch of the coils changes as the number of poles is changed; for instance a two-thirds pitch for four poles means a one and one-third pitch for 8 poles. On this account it is in practice, unsatisfactory to carry the range of speed variation by pole changing beyond the 2 to 1 ratio. The above suggested pitch is on the whole the most satisfactory for a two to one change. It is quite possible to get into serious difficulties by the use of certain other pitches. This method of pole changing results in poor constants at one or both of the speeds, and the controller is usually expensive. Instead of regrouping the coils, the stator may be provided with separate windings of different pole numbers. This method is also expensive.

277. Direct-concatenation and differential concatenation control.* If the secondary of a wound rotor is connected to the primary of another in-

* Danielson, Ernst. "A Novel Combination of Polyphase Motors for Traction Purposes," *Trans.* A. I. E. E., Vol. XIX, page 527.

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duction motor with a short-circuited secondary, and the shafts of the two motors coupled together, the two motors will run at a speed the same as that of a motor having as many poles as the two motors together. This holds if the two rotors tend to revolve in the same direction, which is called connecting the motors in direct concatenation, or direct cascade. If the motors are so connected that the rotors tend to revolve in opposite directions, the speed of the set will be that of a motor having a number of poles equal to the difference of the numbers of poles of the two motors. This connection is called differential concatenation or differential cascade.

278. Possible speed adjustments with concatenation control. Thus it is evident that by connecting two motors of different numbers of poles in either direct or differential concatenation, and by using either motor separately, four different speeds can be obtained. If the second machine has a wound rotor, a resistance can be used to obtain speeds between the different concatenated speeds. By providing each motor with pole-changing windings, it is obvious that the number of speeds may be great. It is rare, however, that this combination is desirable.

279. The chief objection to cascade control is the poor utilisation of material, and the poor operating characteristics. One reason for this is that the exciting volt-amperes of the second motor must be supplied by the secondary of the first motor, and are reflected in its primary. Thus the exciting volt-amperes of the set is the sum of those of the individual motors. Another cause is that the two motors are substantially in series and their reactances add together to furnish the reactance of the set. Thus in the case of two equal motors, their combined output at breakdown will be only half that of one of them alone. In fact it will be less than half, owing to the double exciting current in the first motor. Both causes work to produce an unusually low power-factor. Finally the losses are those of two motors (although some of the losses are less than when the motors are running alone at full-load) with a combined output about one-half that of a single motor. The efficiency is thus very low.

280. Actual operating data of cascade control. These points are illustrated by the curves of Figs. 129 and 130 taken from actual tests: the

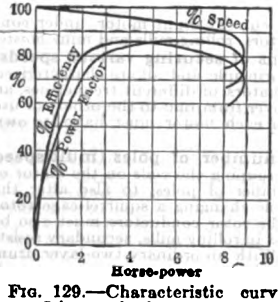


FIG. 129.—Characteristic curves for a 5-h.p. polyphase motor operated direct from the supply.

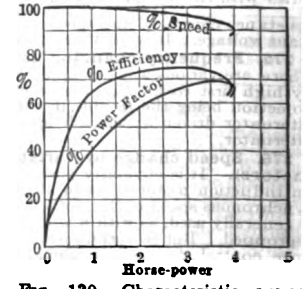


FIG. 130.—Characteristic curves of two motors of the porperties shown in Fig. 129, when operated in cascade.

former for a single 5-h.p. motor, and Fig. 130 for two such motors in concatenation. In this particular case it is not safe to rate the set above 2.5 h.p. because of the early breakdown; but with lower reactance motors, the individual breakdown might easily be 13 h.p. and the concatenated breakdown 6 h.p. This would allow a safe torque-rating of 3.5 h.p., which would also be about the safe rating, on the basis of maximum safe temperature

Whereas the two-speed (by pole changing) motor has a half-speed rating of more than half of its full-speed rating, the concatenated rating of two equal motors is at most only about one-third of the combined full-speed

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motor wound for a 12-pole cascade speed. The stator is provided with ordinary 8-pole winding, divided into sections which are connected in parall The rotor is wound in such a way that either an 8-pole or both an 8-pole a a 4-pole winding can be obtained by either short-circuiting or open circuiti the rotor slip-rings, producing either an 8-pole or a 12-pole speed of the mot The starting rheostat is connected across the rotor slip-rings. The Hu motor gives constant torque at the different speeds, the output being the fore proportional to the speed.

ALTERNATING-CURRENT COMMUTATOR MOTORS

286. Classification. Alternating-current commutator motors may grouped into two classes, as follows:

(a) Those motors in which the resultant *m.m.f.* providing the flux, increas with the load. When operated from a source of constant pressure, the spe of such motors decreases with increasing load. They are termed series motc from the similarity of their characteristics to those of series-wound dire current motors, (b) those motors in which the resultant *m.m.f.* providi the flux, is substantially constant irrespective of the load. For operati from a source of constant pressure, the speed of such motors is approximate constant. The speed may, however, be increased or decreased (indepen ently of the load) by increasing or decreasing the pressure at the termins of the motor, or by the provision of suitably disposed and connected auxilia coils. Such motors are termed shunt motors.

Alternating-current commutator motors are either single phase or pol phase.

287. Single-phase straight series. An ordinary direct-current seri motor if constructed with a well-laminated field circuit, will operate (i though unsatisfactorily) if connected to a suitable source of single-pha alternating electricity. Since the armature is in series with the field, t periodic reversals of current in the armature will correspond with simultan ous reversals in the direction of the flux, and consequently the torque w always be in the same direction. But the inductance of the motor will be so great that the current will lag greatly behind the voltage, and the

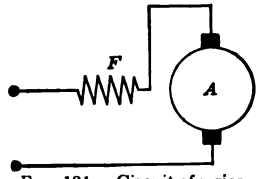


FIG. 131.—Circuit of series motor.

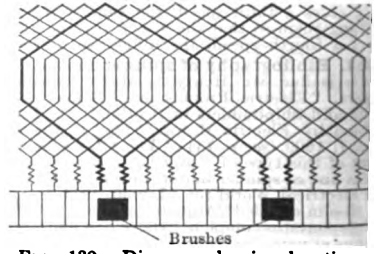


FIG. 132.—Diagram showing location high-resistance leads between the winding the commutator segments.

motor will have a hopelessly poor power-factor. Such a motor is shown grammatically in Fig. 131, in which *F* represents the field and *A* the armat

When the motor is first thrown on the circuit and before the armature moved from rest, the field constitutes the primary of a transformer and s flux through the armature core. Those armature turns which at that ins are short-circuited under the brushes, act as short-circuited secondary and are traversed by heavy currents which serve no useful purpose wha ever and occasion serious heating. As soon, however, as the armature st to revolve, these short-circuited turns are opened as they pass out from u the brushes and they are replaced by other turns which are moments short-circuited and then opened. These interruptions of heavy curr are accompanied by serious sparking since the heating is concentrated at few segments on which the brushes rest. As soon, however, as a cer speed is acquired, the heating is distributed over all the segments and conditions become ameliorated. This source of sparking is, then, most seri

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at the moment of starting. One way in which it has often been sought to decrease this difficulty, has been by the employment of leads of high resistance connecting the winding to the commutator segments as indicated in Fig. 132. The extra-heavy lines in this diagram indicate the coils which, at the particular instant considered, are short-circuited under the brushes. This practice of introducing resistance leads between the winding and the commutator segments has often been carried so far that notwithstanding the brief time during which each lead is in circuit, the loss in the leads has been sufficient to decrease seriously the efficiency, and to constitute a considerable component in the total heating of the motor. Obviously, however, the method affords a means of limiting the short-circuit currents occasioned by transformer action, and consequently improves the commutation during starting.

The alternating current in the intermediate conductors (shown in lighter lines in Fig. 132) is always in such directions relatively to the alternating magnetic flux set up by the field winding, as to occasion in the conductors a force in a constant direction. The motor consequently has the necessary torque and it becomes of interest to investigate means for overcoming its disadvantages. How can the power-factor of the motor be improved; how can we reduce its inductance? We can reduce the inductance of the field winding by employing few turns. This requires designing the magnetic circuit for low magnetic densities (which, in turn, tends to make the motor large and heavy), with small air gaps.

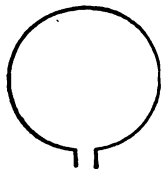


Fig. 133.—Loop of wire with considerable inductance.

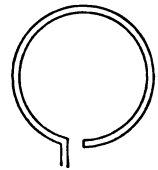


Fig. 134.—Doubled-back loop with negligible inductance.

Single-phase compensated series motor. At the conclusion of Art. 287 we had discussed a way of decreasing the inductance of the field winding. Let us consider now how we may reduce the inductance of the armature winding. A loop of wire, for instance that shown in Fig. 133, has considerable inductance. A doubled-back loop such as that shown in Fig. 134 has but little inductance. The current returning in the doubled-back

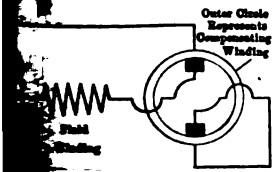


Fig. 135.—Circuits of series-compensated motor. [The inner circle represents the rotor winding and the outer circle represents the compensating winding, which is on the stator.]

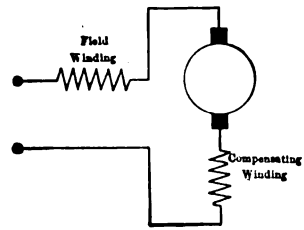


Fig. 136.—Usual diagrammatic representation of a series-compensated motor.

neutralizes the effect of the outgoing current in the first loop. Such a coil is practically non-inductive.

We may crudely imitate this in a motor. If the current after flowing through all the turns of the armature winding is compelled to flow in the re-

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verse direction through a winding of just the same number of turns arranged in as close proximity as possible to the armature winding, then the magnetomotive force of the second (or compensating winding) balances the magnetomotive force of the armature winding, that is to say, it renders it non-inductive. Unfortunately in applying this principle to our single-phase motor, we are constrained to locate the compensating winding on the stator, *i.e.*, on the side of the air gap remote from the armature winding. Consequently, we fall considerably short of rendering the system *completely* non-inductive; nevertheless, it is by means of this plan that single-phase motors are made commercially effective. In order to obtain the best results, the compensating winding should be distributed around the stator surface similarly or equivalently to the manner in which the armature winding is distributed around the rotor surface. It does not suffice to have the same *total m.m.f.* in each, but it is important that, *at each part* of the periphery, the neutralization shall be as complete as practicable. The arrangement may be indicated as shown in Fig. 135, in which the outer circle represents the compensating winding. For diagrammatic purposes, however, it is more usual to replace the outer circle by a coil whose axis is in the direction of the *m.m.f.* set up in the compensating winding when the current flows through it. Whereas the main field coil is in space-quadrature with the *m.m.f.* of the armature winding, the *m.m.f.* of the compensating winding is in the same space phase as the armature *m.m.f.*, but in the opposite direction. In Fig. 136 the compensating winding is represented diagrammatically by a coil with its axis coinciding with the brush axis. That this is the required location may be more clear if attention is drawn to the fact that the armature winding, considered by itself, constitutes a source of *m.m.f.* whose direction is in a line through the brushes. Whatever the actual form adopted for the armature winding, it is at any instant equivalent to the winding shown in Fig. 137 as far as it relates to its *m.m.f.* Assembling around the armature, the field coil and the compensating coil in their appropriate angular positions, as in Fig. 138, we obtain an instructive diagrammatic representation of a single-phase compensated series motor.

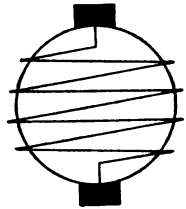


FIG. 137.—"Equivalent" armature winding.

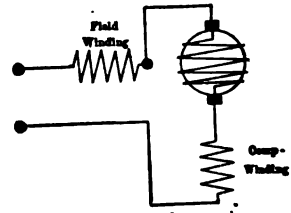


FIG. 138.—Diagram of a series-compensated motor indicating that the compensating winding lies in the same axis as the "equivalent" armature winding, and opposes it

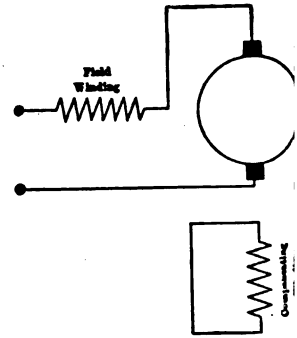


FIG. 139.—Inductively compensated series motor.

289. Inductive and conductive compensation. Compensation may be "conductive," as shown in Figs. 135, 136, and 138, or it may be "inductive

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as shown in Fig. 139. With the latter arrangement the compensating currents are induced in the short-circuited compensating coil just as current is induced in the short-circuited secondary of a transformer. And similarly as in the case of the transformer, the secondary current automatically rises to such a value as to occasion a *m.m.f.* approximately equal and opposite to the primary *m.m.f.* But "conductive" compensation is preferable, for it permits of control and adjustment of the compensating *m.m.f.* Under some circumstances it is desirable to be able to *over*compensate, *i.e.*, to set up in the compensating coil a *m.m.f.* which shall slightly exceed the armature *m.m.f.* This is readily effected with "conductive" compensation, but not with "inductive" compensation.

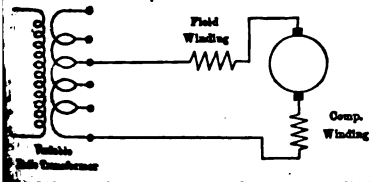


Fig. 140.—Series-compensated motor supplied from a variable-ratio transformer.

290. Speed control. Fairly good single-phase motors have been constructed on the principles which have been set forth in Par. **288** and **289**. Such motors have series characteristics, their speed decreasing as their load increases. This must obviously be the case, for the field excitation is occasioned by the flow of the armature current through the field winding. Thus the flux increases with the load and the armature will decrease in speed since the counter e.m.f. must, as in a direct-current motor, be slightly less than the terminal voltage. But, while for a given terminal voltage, the speed decreases with increasing load; nevertheless we can readily arrange that such a motor shall, for any load, be operated at any desired speed over quite a wide range. This is done by supplying the motor from taps out of a transformer in the main circuit. The arrangement is shown diagrammatically in Fig. 140. By varying the position at which the adjustable terminal of the transformer is tapped into the secondary of the transformer, we can vary the voltage impressed on the motor and thus readily control and adjust its speed. An alternating-current series motor has in this respect an important advantage over a direct-current series motor, since in the latter the speed control can

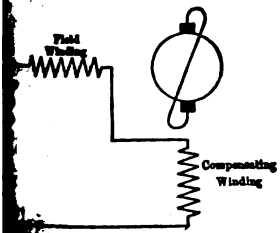


Fig. 141.—The Atkinson repulsion motor.

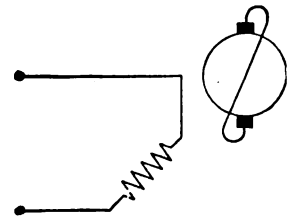


Fig. 142.—The Thomson repulsion motor.

controlled simply only by varying the amount of resistance in series with the motor, and consequently with a serious loss in efficiency.

Single-phase repulsion motor. It is only a step from the inductively compensated motor illustrated in Fig. 139 to a motor in which current is induced in the armature circuits by means of the *m.m.f.* set up in the compensating winding when current is sent through it. The motor at which we now arrive is shown diagrammatically in Fig. 141. Instead of short-circuiting the compensating winding, we short-circuit the armature winding. In other words we simply exchange the relations of compensating winding and armature winding which were shown in Fig. 139.

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292. Evolution of the repulsion motor. The connection shown in Fig. 141 is known as the **Atkinson repulsion motor.** It was suggested by Atkinson many years after the invention by Prof. Elihu Thomson of the *simple* repulsion motor. In the original **Thomson repulsion motor** the field coil and the compensating coil shown in Fig. 141 find their equivalent in a single coil which may be looked upon as supplying a *m.m.f.* of which the field *m.m.f.* and the compensating *m.m.f.* in Fig. 141 are the components. The Thomson repulsion motor is shown in Fig. 142. The stator coil has, in this figure, been drawn in a position intermediate between the positions of the compensating coil and the field coil in Fig. 141 in order to emphasize the idea that these two component coils have been replaced in magnitude and direction by their resultant. As must be evident from the nature of its evolution, the Thomson repulsion motor also has the characteristic of a series motor in that its speed decreases with increasing load.

293. Single-phase compensated repulsion motor. Many pioneers in the design of direct-current motors have long ago sought to bring the field coil close down around the armature in order to obtain the full effect of the field *m.m.f.* right at the armature where it is desired. Eickemeyer's name is closely associated with designs of this sort. What could more closely approximate to the desired result than to employ the armature winding itself as the locus for the excitation? Several inventors conceived this idea practically simultaneously. They accomplished their purpose by applying to the

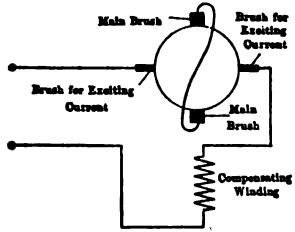


FIG. 143.—Compensated repulsion motor. [Latour-Winter-Eichberg.]

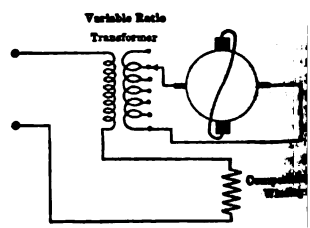


FIG. 144.—Compensated repulsion motor supplied from a variable-ratio transformer.

commutator a second set of brushes situated in quadrature with the main brushes and sending the exciting current through the armature winding by means of these additional brushes as shown in Fig. 143, which should be contrasted with the Atkinson repulsion motor of Fig. 141. It will be seen that the field coil has been eliminated from the stator circuit, and that its function has been assumed by the armature winding through which the current is carried by means of the two auxiliary brushes. The arrangement shown in Fig. 143 is termed a compensated repulsion motor. This motor also has a series characteristic.

It would seldom or never be convenient to wind the armature of Fig. 143 with the particular number of turns which is suitable for the field excitation. Consequently it becomes necessary to supply the excitation from the secondary of a transformer whose primary is in series with the compensating winding. This arrangement, which is shown in Fig. 144, has the further useful feature of permitting speed control by varying the point at which the field excitation circuit is tapped off from the secondary of the transformer. The compensated repulsion motor illustrated in the above two figures was independently invented by Latour in France and by Winter and Eichberg in Germany. It would be futile to undertake here an enumeration of the dozens of variations in the above fundamental types of single-phase commutator motors with a series characteristic.

294. Polyphase commutator motors with a series characteristic. In Fig. 145 is shown the simplest form of **Görges three-phase motor.** Its rotor has an ordinary direct-current winding with a commutator

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which rest three equidistant brushes per pair of poles. The diagram indicates a bipolar motor. The brushes are connected to the terminals of the three stator windings, which, in turn, are supplied either directly from the line, or else, as indicated in the diagram, from the secondary of a step-down transformer. Usually the most suitable voltage for the stator windings will be higher than that most suitable for the commutator. Consequently, the arrangement shown in Fig. 146 is often to be preferred. This latter arrangement permits of employing, for the rotor, the low voltage which is essential to obtaining good commutation. Such motors have a series characteristic; that is to say, the speed decreases as the load increases.

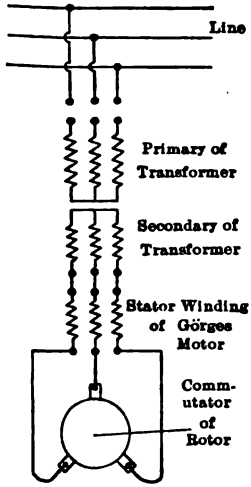


FIG. 145.—Görges motor with transformer between line and stator windings.

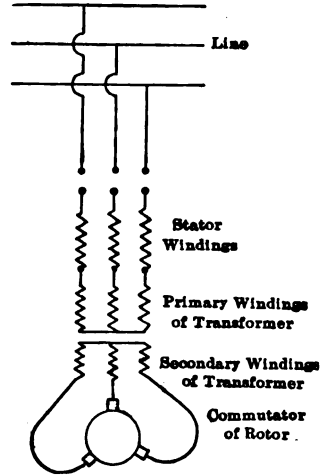


FIG. 146.—Görges motor with transformer between stator and rotor.

256. Variable-speed polyphase commutator motors. The speed can be adjusted, for any load, by shifting the brushes through an appropriate angular distance, maintaining the 120-deg. relation between the three brushes. This is done in the General Electric Co.'s brush-shifting type of variable-speed polyphase motors. See also, "The Brush-shifting Polyphase Series Motor," by W. C. K. Altes at pp. 115 and 199 of *General Electric Review* for 1916 (Vol. XIX).

256. Compensation of polyphase commutator motors with series characteristics. For the reasons already discussed in connection with the compensation of single-phase commutator motors, it is of advantage in polyphase commutator motors to fit them with compensating windings at right angles to the exciting windings. The cost, however, is necessarily increased, and in America the use of compensating windings is not customary for such motors. The arrangement, when compensating windings are employed, is indicated diagrammatically in Fig. 147, in which the three exciting windings $a^1b^1c^1$ on the stator are supplied from the three lines *abc*. After passing through the three exciting windings the current passes through the compensating windings *def* which are located with their magnetic axes in line with the magnetic axes of the rotor brushes. The addition of these compensating windings improves the power-factor and permits of obtaining better commutation. Since the most suitable voltage for the main field windings on the stator will often be different from that most suitable for the commutator, and for the compensating windings on the stator, it would be preferable to

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employ in place of the arrangement indicated in Fig. 147 a modified arrangement in which the main field windings are located between the supply circuit and the primary windings of the transformer, while the compensating and rotor windings, connected in series, are supplied from the secondary of the transformer.

297. Single-phase commutator motors with a shunt characteristic for operation at a single speed. The only object in employing a commutator in the construction of a single-phase motor to operate at but one constant speed, is to provide control of the power-factor. Otherwise the single-phase induction motor with a squirrel-cage rotor would be preferable. The Atkinson commutator induction motor indicated diagrammatically in Fig. 148 is the forerunner of all single-phase commutator motors with shunt characteristics. It consists of a stator with a distributed winding, and a rotor fitted with a commutator and with two sets of short-circuited brushes xx and yy. There is no torque when the motor is at rest. If, however, the motor is started in either direction, interactions occur which occasion in the xx axis a current in phase with the line voltage applied to the stator. This current sets up a flux along the xx axis. As the rotor acquires speed, the current induced in the yy axis by the stator winding, comes more nearly into phase with the flux in the xx axis and consequently the torque increases. In this motor the torque increases in proportion to the speed, from the zero value corresponding to standstill. When the speed of the rotor nears synchronism, the motor is equivalent to a squirrel-cage induction motor, except that in place of having end-rings effecting a good simultaneous short-circuit of all the rotor conductors, there are only two short-circuiting connections by means of the two pairs of brushes. Obviously there is no feature in this *elementary*

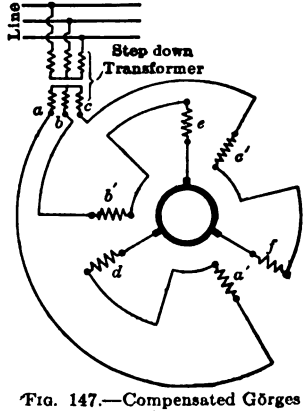


FIG. 147.—Compensated Görges motor.

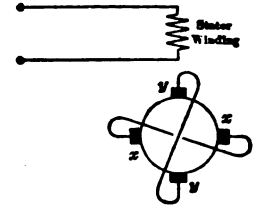


FIG. 148.—Atkinson commutator induction motor.

commutator motor which will improve the power-factor as compared with that of the single-phase squirrel-cage induction motor.

298. Compensation of single-phase commutator motors with shunt characteristics. Various inventors have indicated methods of "compensating" such a motor, *i.e.*, of improving its power-factor. These methods resolve themselves into the following classification: (a) introducing in the circuit of the yy brushes a stator winding in the xx axis; (b) introducing in the circuit of the xx brushes a stator winding in the yy axis; (c) introducing in the circuit of the xx brushes an e.m.f. in phase with the line pressure. These three methods are shown in Figs. 149, 150, and 151.

299. Single-phase commutator motors with a shunt characteristic and an adjustable speed. There is quite a demand for single-phase commutator motors with a shunt characteristic and with means for adjusting the speed. For any particular adjustment the speed will be substantially constant at all loads. The usual methods for accomplishing this are based upon the investigations of Punga, Fynn, Creedy and Milch. The simplest method consists in introducing in the yy axis an electromotive force of the same phase as the line pressure. This may be done by means of a transformer, as shown in Fig. 152. If the secondary coil A in the above figure provided

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m.m.f. acting in the same direction as the coil B, the speed of the motor will be increased. If A is connected to oppose B, the speed of the motor will be decreased. Speed control may also be obtained by introducing into the

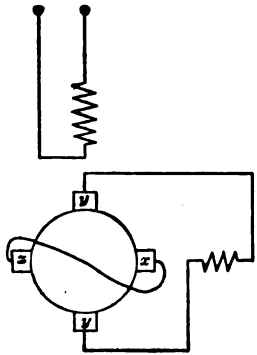


FIG. 149.—Single-phase commutator motor with *power-factor*-modifying coil supplied from the *yy* brushes.

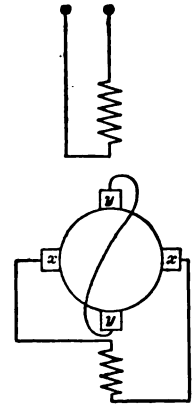


FIG. 150.—Single-phas commutator motor with *power-factor*-modifying coil supplied from the *xx* brushes.

circuit of the *xx* brushes a stator winding A located in the *xx* axis as shown in Fig. 153. Connecting A in the one direction increases the speed: connecting it in the other direction decreases the speed. Still another method of obtaining speed control is shown in Fig. 154 and is the invention of Creedy. In this case the field along the *xx* axis is weakened or strengthened and the speed varied, by varying the amount of inductance or capacity in the circuit of the *xx* brushes.

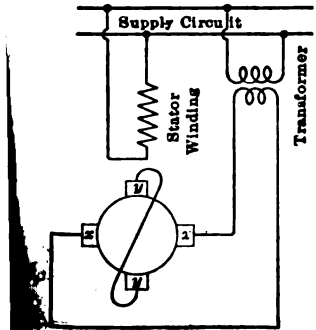


FIG. 151.—Single-phase commutator motor with *power-factor* modified by an e.m.f. interpolated in the *xx* axis by means of a transformer supplied from the line.

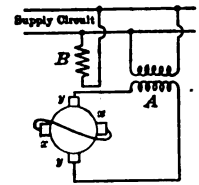


FIG. 152.—Single-phase commutator motor with *speed* modification by means of an e.m.f. interpolated into the *yy* axis by means of a transformer supplied from the line.

300. Single-phase repulsion-starting induction motor (Arnold motor). This motor which is built under the patent of the late Prof. E. Arnold of Karlsruhe, in Germany, is extensively used in the United States.

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The connections at starting are those for a repulsion motor as shown in Fig. 142, the brush axis standing at an angle with the axis of the stator winding and the brushes being short-circuited. This connection permits of starting with high torque. When a certain speed is attained, a centrifugal governor acts to short-circuit all the commutator segments and to remove the brushes from the commutator. The motor then operates just like a squirrel-cage

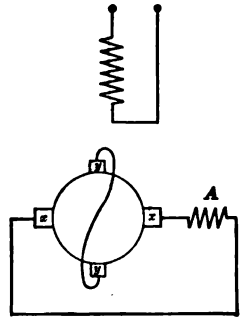


FIG. 153.—Single-phase commutator motor with speed modification by means of a coil fed from the *xx* brushes and located on the stator in the *xx* axis.

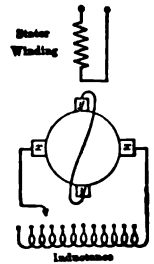


FIG. 154.—Creedy single-phase commutator motor with speed variation by inductance in the *xx* circuit.

induction motor and maintains approximately constant speed at all loads. It is usually preferable to employ starting boxes in sizes above 7.5 h.p., but smaller sizes are usually thrown directly on the line. The motors develop a starting torque (when thrown directly on the line) of some 250 per cent. of full-load torque, consuming approximately 250 per cent. of full-load current. (See Fig. 155.)

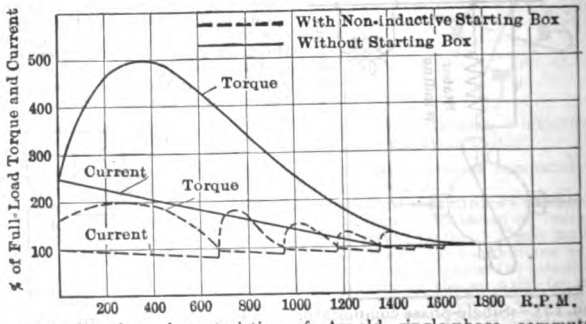


FIG. 155.—Starting characteristics of Arnold single-phase commutator motor. (Taken from the manufacturer's publications.)

301. Motor with repulsion starting, gradually converted into "induction" operation. (Schüler motor.) This type was developed by Schüler for the Ferranti Co. in England. It started as a repulsion motor and was gradually converted into a single-phase induction motor by the gradual decrease in resistances connected to slip-rings. These resistances

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are great at starting and are reduced to zero at full speed. This sequence of operations results in giving the motor excellent characteristics. The Schüler motor is described on pp. 712 to 720 of the 2nd edition of Hobart's "Electric Motors."

302. The Wagner "Unity Power-factor" Type BK motor. In 1911 the Wagner Electric Co. placed upon the market a constant speed single-phase commutator motor so constructed as to provide a leading power-factor at no-load and at light loads, and unity power-factor at rated load. The arrangement is represented diagrammatically in Fig. 156. As indicated in this diagram there are two stator windings 1 and 2. During starting, the switch (9) is open, so that only the stator winding (1) is in circuit. The motor consequently starts up with good torque

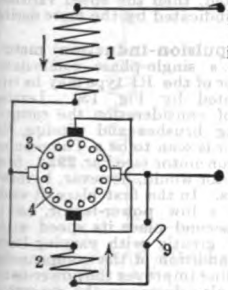


FIG. 156.—Diagrammatic representation of the Wagner "Unity-Power-Factor" (Type BK) motor. 1.—Initial field magnetization winding. 2.—Auxiliary winding which controls the power-factor or compensates the motor.

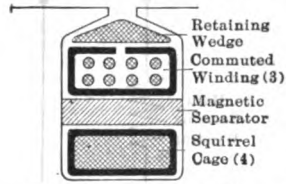


FIG. 157.—Diagrammatic representation of design of rotor slot of Wagner "Unity-Power-Factor" (Type BK) motor.

as a series motor. The rotor slot design is shown in Fig. 157. During starting, the squirrel-cage winding (4) is more or less inert as it is protected by the magnetic separator shown in Fig. 157. The magnetic separator is described in the manufacturer's publications as consisting of a rolled-steel bar. The upper winding (3) is termed a "commuted" winding. It is connected to a commutator in the manner usual in direct-current motor armatures. As speed is acquired, the activity of the squirrel cage increases, and it contributes a torque which increases very rapidly as synchronism is approached.

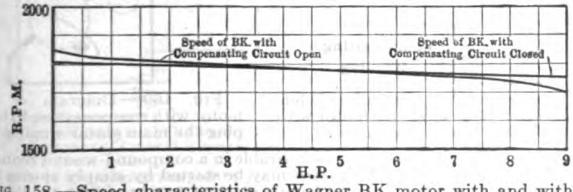


FIG. 158.—Speed characteristics of Wagner BK motor with and without compensating winding in circuit.

An automatic switch controlled by centrifugal force closes the circuit of the compensating winding (2) when a sufficient speed has been attained.

303. Commendable features of the unity power-factor motor. (a) "A large portion of the rotor currents are carried by the squirrel-cage winding, in normal operation, thus imposing light-load service on the commutator." (b) "The close proximity of the squirrel-cage to the commuted winding suppresses to a large extent the short-circuit currents which tend to flow in the individual coils of the commuted winding as they pass under the brushes. This again very greatly lightens the commutator service." (c) "The employment of the squirrel cage secures a remarkably constant

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speed at all loads." This is indicated in Fig. 158 in which are plotted speed curves for the compensating circuit open and closed. (d) "The squirrel cage absolutely prevents the unity power-factor motor from running away or racing. No possible accident to the commutator, brush gear or automatic switches of this motor can cause the speed variations between no-load and full-load to exceed 4 per cent. When the compensating circuit (which includes the winding 2 of Fig. 156) is closed, the speed variation is shown by the least sloping curve of Fig. 158 and does not exceed 1.5 per cent. Should the compensating circuit be entirely interrupted, then the speed variation will not increase to more than 4 per cent., as indicated by the more sloping curve of Fig. 158."

304. The General Electric Co.'s RI (repulsion-induction) motor. Diagrammatically the General Electric Co.'s single-phase commutator motor of the RI type may be represented by Fig. 159. Leaving out of consideration the compensating brushes and winding, the motor is seen to be a Thomson repulsion motor (see Par. **292**). Such a motor would, however, have two faults. In the first place, it would have a low power-factor, and in the second place its speed would vary greatly with varying loads. The addition of the compensating winding improves the power-factor and also decreases the amount of the variation of the speed with the load. The motor is not designed for constant speed but for such a moderate decrease in speed

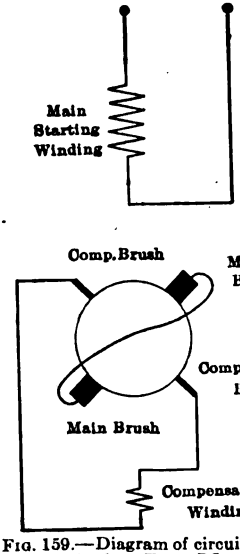


FIG. 159.—Diagram of circuits of General Electric Co., Type RI motor with independent compensating circuit.

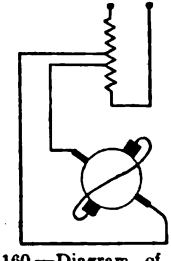


FIG. 160.—Diagram of RI motor with compensation by tapping the main stator winding.

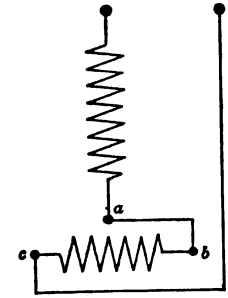
with increasing load as is considered desirable in a compound-wound continuous-electricity motor. An RI motor may be started by simply closing the line circuit of the motor. It will have a starting torque of 200 to 250 per cent. of full-load torque. If it is desired to reduce the starting current, a resistance box with low-voltage release may be used. This is proportioned to give 150 per cent. of full-load current on the first step. These motors are built for 25, 40 and 60 cycles and for synchronous speeds (at 60 cycles) of 1,200 and 1,800 rev. per min. See Altes, W. C. K. and Currie, N., "Single-phase Alternating Current Motors," *General Electric Review*, Vol. XIX (1916), p. 579.

305. Compensation. In some of the smaller sizes the compensation is obtained by taps from the main winding instead of from a separate winding as shown in Fig. 159. The tapped arrangement is indicated diagrammatically in Fig. 160.

306. In reversible repulsion-induction motors (Par. 304) an auxiliary winding in space-quadrature with the main winding is provided. This

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winding is connected in the one or the other direction with respect to the main winding according to the direction of rotation desired. The scheme is indicated diagrammatically in Fig. 161. To reverse the direction of rotation, *a* would be connected to *c*, and *b* would be connected to *d*. It is to be observed that in Fig. 161, the axis of the main brushes coincides with the axis of the main stator winding but has the same angle to the resultant of the main and reversing stator windings, which, in Fig. 159, it had with the main stator winding. Were no reversing winding provided, then in order to reverse the direction of rotation it would be necessary to shift the brushes over to the corresponding angle on the other side from the position for normal direction of rotation.



307. Repulsion-induction motors may be fitted for adjustable-speed operation (Par. **299**) by employing a transformer with its primary excited from the line circuit and its secondary interpolated in the circuit of the energy brushes. Such motors are arranged for a speed range of about 2 : 1, approximately one-half of this range being below and one-half above synchronous speed. Finally,

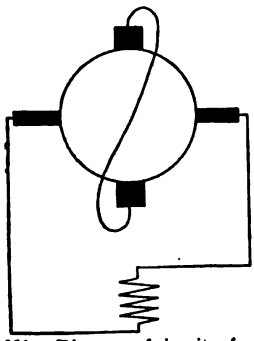


FIG. 161.—Diagram of circuits of reversible RI motor (General Electric Co.).

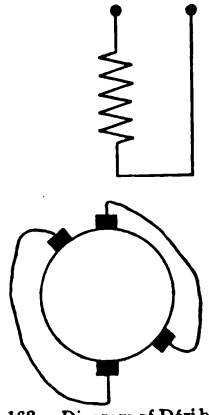


FIG. 162.—Diagram of Déri brush-shifting motor.

RI motors are also arranged to give variable speed by shifting the brushes. A speed variation of 2 : 1 is provided in this way.

308. The Déri single-phase motor with speed control by brush shifting. Fig. 162 is a diagrammatic representation of the Déri single-phase motor. In this motor the speed is varied by varying the position of the brushes. Two of the brushes (those lying in the axis of the stator winding) are of fixed position. The other two are mounted on a movable yoke. For any given brush position the speed decreases with increasing load. Thus the motor has a series characteristic. The motor has good starting torque, the maximum value occurring when the movable brushes are at an angle of some 150 deg. to 160 deg. from the fixed brushes.

The motor is widely employed abroad for driving textile machinery. The simple mechanical arrangements required to effect the shifting of the brushes are less expensive than equivalent control devices which permit of

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accomplishing the speed variations without brush movement. Schnetzler has described the Déri motor in a paper published in the E. T. Z. for Nov. 14 and 21, 1907 at pp. 1097 and 1128. There is also a description of the Déri motor occupying pages 669 to 685 of the 2nd Edition of Hobart's "Electric Motors."

309. The Punga-Creedy single-phase commutator motor. Adjustable-speed, single-phase, commutator motors built under the Punga-Creedy patents have been placed on the British market by Messrs. F. Parkinson & Co., of Leeds. The motor is started by being thrown directly on the line and yields a starting torque of twice full-load torque, consuming twice full-load current. Figs. 163, 164 and 165 show (1) the speed-torque, (2) efficiency, and (3) power-factor curves for a 6-h.p. Punga-Creedy motor for printing-press work. Allusion has already been made in Par. 289 to the principles employed in motors of this class. The chief patents employed in the Punga-Creedy system are Punga's British Patent No. 10585 of 1906 and Creedy's British Patent No. 5136 of 1906. Punga and Creedy tested motors embodying these principles at early dates. The results of a number of these tests have been published in the *Trans.* A. I. E. E., Vol. XXVIII (1909), p. 475, in a paper by Creedy entitled "A sketch of the theory of adjustable-speed, single-phase commutator motors."

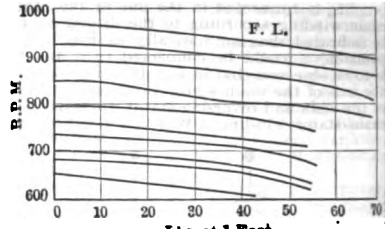


FIG. 163.—Speed-torque characteristics of a 6-h.p. Punga-Creedy single-phase motor for printing-press work. [Speed range is from 600 to 900 rev. per min.] [Messrs. F. Parkinson & Co. of Leeds, England.]

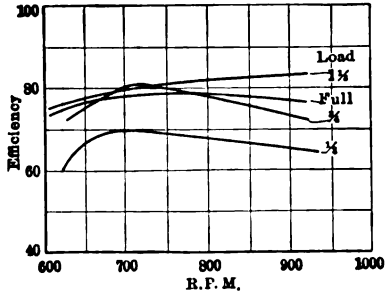


FIG. 164.—Efficiency curves for a 6-h.p. Punga-Creedy single-phase motor for a speed range from 600 to 900 r.p.m. [Messrs. F. Parkinson & Co. of Leeds, England.]

310. Polyphase shunt commutator motors. The most usual arrangement of a polyphase shunt commutator motor is that known as the **Winter-Eichberg type.** It is shown diagrammatically in Fig. 166 and is seen to consist of a motor with a three-phase stator and a commutator rotor. The speed will depend upon the pressure applied to the commutator brushes. By using a

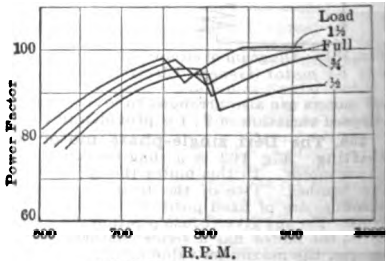


FIG. 165.—Power-factor curves for a 6-h.p. Punga-Creedy single-phase motor for a speed range from 600 to 900 rev. per min. [Messrs. F. Parkinson & Co. of Leeds, England.]

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variable-ratio transformer as indicated in the diagram, the speed will be greater, the smaller the secondary voltage applied to the brushes. Such motors have not come into extensive use. They are large and expensive for their output and the cost for the variable-ratio transformer is a serious consideration. The whole equipment will cost over twice as much as an equivalent continuous-current equipment.

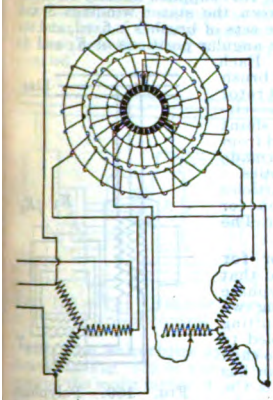


FIG. 166.—Diagrammatic representation of Winter-Eichberg type of polyphase shunt commutator motor.

311. Quarter-phase shunt commutator motor with adjustable speed by field control. In Fig. 167 is shown a type of motor in which the compensating winding and the armature winding are fed from one phase of a quarter-phase system while the exciting winding is fed from the other phase. Since the compensating and armature winding constitute a circuit of low inductance, the current in this circuit is practically in phase with the pressure of the circuit from which they are supplied. But the exciting circuit is highly inductive and its current lags practically 90 deg. behind the pressure of the circuit to which it is connected and 180 deg. behind the current in the armature. The armature current and the magnetic flux are consequently in phase, just as in a simple single-phase series motor. The motor is thus the equivalent of a direct-current motor with shunt excitation. Its speed for any given field strength is practically constant at all loads. But any desired speed can be obtained by inserting reactance of suitable amount in series with the excitation winding. Speed control can also be obtained by supplying the main circuit from a variable-ratio transformer. On page 2488 of Part III of Vol. XXX (1911) of the *Trans.* A. I. E. E., Mr. B. G. Lamme discusses this type of motor and alludes to a 20-h.p., 25-cycle motor built in this way which gave excellent satisfaction and with which the speed was adjustable from practically zero up to 1,000 rev. per min. The speed was controlled by adjustable armature pressure from transformers.

Mr. Lamme also mentions the equivalent arrangement shown in Fig. 168. In this arrangement the armature circuit instead of being conductively

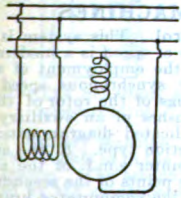


FIG. 167.—A type of quarter-phase, variable-speed commutator motor.

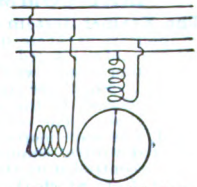


FIG. 168.—A modified type of quarter-phase, variable-speed, commutator motor.

connected to the supply as in Fig. 167, is closed on itself, the armature current being set up by induction from the winding which, in Fig. 176, served as compensating winding.

312. The polyphase commutator motor with shunt characteristics and with speed control by brush shifting. The expense of the control arrangements limits the application of variable-speed polyphase motors of

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types of which that described in Par. 310 (Winter-Eichberg) is representative. It is often considered that brush-shifting types are preferable. One such type which is exploited by the Siemens-Schuckert-Werke and is described by Schenkel on pages 1059 and 14 of the *Electrician* for Oct. 4 and 11, 1912, is illustrated diagrammatically in Fig. 169. In this figure, the stator windings are represented by S. These windings are (in the particular variety illustrated in Fig. 169) supplied directly from the line. A transformer T is interposed between the stator windings S and the rotor brushes K_1 and K_2. One of these sets of brushes is fixed, and the other is movable. By varying the relative angular positions of K_1 and K_2 the speed of the motor may be controlled. Each of the two brush gears is fitted with three brush spindles per pair of poles for multiple-circuit rotor windings, or some suitable equivalent for two-circuit rotor windings. These motors have shunt characteristics and are to be distinguished from the Görges motors to which reference has been made in (Par. 294), which have series characteristics.

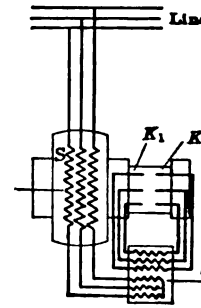


FIG. 169.—Polyphase commutator motor with speed control by brush-shifting.

Such motors are the subject of other articles published by Rüdenberg in the *Electrician* for April 7 and July 21, 1911, and by Meyer in The *Electrician* for Feb. 2 and 9, 1911.

313. The Déri brush-shifting motor for polyphase circuits. It is often considered that for obtaining variable speed drive from polyphase circuits, the best plan consists in employing two Déri single-phase motors (of the brush-shifting type already described in Par. 308), coupled to the same shaft and connecting one motor to each phase of a quarter-phase system. This plan has been employed by Messrs. Brown, Boveri & Co. Among other applications of the method may be mentioned some heavy hoisting work.

313(a). Bibliography of polyphase commutator motors.

ALTES, W. C. K.—"The Polyphase Shunt Motor," *Trans.* A. I. E. E., Vol. XXXVII (1918), Part I, p. 295.

KARAPETOFF, V.—"The Secomor, a Kinematic Device which Imitates the Performance of a Series-wound Polyphase Commutator Motor," *Trans.* A. I. E. E., Vol. XXXVII (1918), Part I, p. 329.

SHUTTLEWORTH, N.—"Polyphase Commutating Machines and Their Application," *Jour.* I. E. E., Vol. 53 (1915), p. 439.

SYSTEMS OF SPEED CONTROL REQUIRING AUXILIARY COMMUTATING MACHINES

314. The Krämer system of speed control. This system is appropriate for applications where the desired range of speed is a moderate percentage of the normal speed. It consists in the employment of a single slip-ring induction motor which at practically synchronous speed carries the entire load. For lower speeds the slip-rings of the rotor of the main motor supply energy to the commutator brushes of an auxiliary motor on the same shaft. The arrangement is indicated diagrammatically in Fig. 170. A, the main motor, is of the induction type. B, the auxiliary motor, is fitted with a commutator. The counter e.m.f. of the auxiliary motor may be controlled by the position of the points of the secondary of a transformer C from which the connections to the commutator brushes are tapped off. In American practice, however, it is much more usual to make use of a small direct-connected polyphase exciter similar in design to the auxiliary regulating motor, as shown in Fig. 171, where the stator of the exciter C is supplied from the slip-rings of the main motor A, through a three-phase resistor D. Speed control is obtained by manipulation of the resistor and a far larger number of running points is provided than is commercially practicable with the transformer arrangement shown in Fig. 17[illegible]. The greater the counter e.m.f. supplied by B, the lower will be the speed of the rotor of A and consequently also, of the shaft common to A and B. The load carried by B is proportional to its counter e.m.f., consequently B's cont[illegible]

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The use of an independent high-speed set which can be readily transferred to some other motor if subsequent conditions make the change desirable, is also an advantage. While the Krämer system possesses some advantage under conditions involving the full kilowatts output at the lowest speed and high *synchronous* speed, this advantage often disappears where slow-speed motors are concerned.

316. Synchronous converter method of speed control. As stated above, the permissible range of speed regulation with either the Krämer or Scherbius system as described, is limited by the maximum frequency which can be successfully applied to the regulating motor without excessive commutation stresses. In general this frequency should not exceed 18 to 20 cycles or approximately 30 per cent. regulation for 60-cycle systems, and from 10 to 12½ cycles or approximately 50 per cent. regulation for 25-cycle systems. Where greater ranges are required or with units involving a slip energy of 1,000 kw. or more, a synchronous converter and direct-current motor can be successfully substituted for the polyphase commutator motor. In this case (Fig. 173) the slip energy of the main motor *A*, at varying frequency and voltage is transformed to direct current at proportionately varying potential by a synchronous converter *B*. This direct current is then utilized to drive a separately excited shunt motor *C* which may be direct-connected on the shaft of the main motor (Krämer), or (Fig. 173) may form one unit of (*CD*), a two-unit motor-generator (Scherbius), the second unit of which (*D*) is a standard squirrel-cage induction motor which, driven above synchronism, acts as an induction generator and returns to the system the slip energy of the main motor, less, of course, the losses in the rotary and motor generator. This arrangement can be used for practically any range of speed reduction which may be desired. It is of especial advantage on 60-cycle systems, not only because of the freedom from difficulties encountered with the commutator motor when subjected to higher frequencies but also due to the fact that the limitation imposed by the minimum frequency at which the synchronous converter will remain in synchronism is less objectionable on 60-cycle than on 25-cycle equipments. With suitable electrical and mechanical devices for controlling the speed of the synchronous converter during the unstable period of minimum impressed frequency corresponding to the interval between approximately 2 cycles above and below the synchronous speed of the main motor, the speed of the main motor can be raised above normal synchronism by an amount corresponding to the frequency impressed on the slip-rings by the now-inverted synchronous converter.

317. Bibliography of systems of speed control requiring auxiliary commutating machines.

Pages 2483 to 2484 of Part III of Vol. XXX (1911) of *Trans.* A. I. E. E. in a paper by G. A. Maier entitled "Methods of Varying the Speeds of Alternating-current Motors."

Trans. A. I. E. E., Vol. XXXI (1912) p. 2067, by F. W. Meyer and Wilfred Sykes entitled "The Economical Speed Control of Alternating-current Motors Driving Rolling Mills."

F. B. CROSBY.—"Speed Control of Polyphase Motors." *General Electric Review* for June, 1914, pages 589 to 599.

PHASE MODIFIERS

318. Definition. In order to correct for the lagging current consumed by induction motors and other inductive apparatus, and thus improve the power-factor of a system, apparatus known as phase modifiers (or phase controllers), may be employed. These are of two classes, synchronous, and non-synchronous.

319. Synchronous phase modifiers (usually termed synchronous condensers) are of the same general construction as synchronous motors, except that they need not be proportioned to deliver power from the shaft and that their fields should be proportioned for a wide range of excitation.

320. The usual method of employing synchronous condensers consists in installing them to float on the line. They are overexcited so as to draw a current leading the pressure by nearly 90 deg. This current neutralizes an equal amount of lagging component due to other apparatus on the system, such as induction motors and lightly loaded or unloaded transformers. If designed with the necessary mechanical strength, synchro-

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nous condensers may simultaneously operate as motors and it is customary to proportion them to thus operate to the extent of a consumption of 70 per cent. of their rated kv-a. They can, when thus operating, be so excited that they also draw from the line, as leading wattless kv-a., 70 per cent. of their rated capacity in kv-a. thus effecting power-factor improvement at the same time that they are serving as motors to deliver mechanical energy. Synchronous condensers are fitted with amortisseur windings to improve their starting qualities and to serve in preventing surging and hunting.

321. Non-synchronous phase modifiers (or phase controllers). Several varieties of apparatus customarily called phase advancers, have been developed for use in connection with individual induction motors for the purpose of improving their power-factor. Such apparatus is supplied with very low frequency electricity from the secondary windings of the induction motors. The frequency is that corresponding to the "slip" of the induction motor. Such phase advancers have an inherent characteristic which may conveniently serve to distinguish them from synchronous condensers (Par. **319** and **320**). This characteristic is that they are *not synchronous machines*.

Leblanc was probably earliest in drawing attention to methods of securing phase control by the use of non-synchronous auxiliaries. His proposals may be explained by reference to the accompanying diagrams. In Fig. 174, *AC* and *BD* represent two series-excited machines which, by suitable mechanical means, are driven at some appropriate speed. The field *C* of *AC* and the armature *B* of *BD* are connected in series with phase *N* of the quarter-phase rotor *MN*. Similarly, the field *D* of *BD* and the armature *A* of *AC* are connected in series with the other phase, *M*. Thus the current

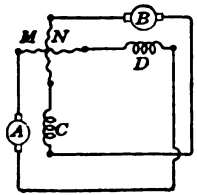


FIG. 174.—Leblanc phase advancer with two armatures and fields.

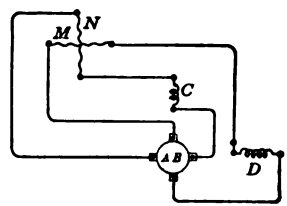


FIG. 175.—Leblanc phase advancer with a single armature.

for exciting the field surrounding each armature is displaced 90 deg. from the current in the phase with which the armature is in series. The armature pressure is consequently 90 deg. displaced from the pressure of the rotor winding with which it is in series. The resultant pressure and current in each rotor circuit, can, by these means, be displaced by any desired amount from the phase relations which would subsist were the rotor windings merely short-circuited on themselves in the customary way. Obviously, the greater the speed at which *A* and *B* are driven and the greater the *m.m.f.* provided by *C* and *D*, the more may the resultant pressures (and, consequently, also the currents) be advanced in phase from the conditions subsisting with a normally short-circuited rotor without a phase advancer.

In practice, however, it is more convenient to employ a single armature, as indicated in Fig. 175, and to supply its commutator (assuming a bipolar design of phase advancer) with four brushes. The armature *AB* (Fig. 175) may be either directly mounted on the motor shaft or it may be driven at a suitable speed by an auxiliary motor. The currents supplied to the brushes will be of the low frequency corresponding to the slip of the rotor *MN* of the induction motor whose power-factor it is desired to improve. Fig. 176 differs from Fig. 175 simply in that a field structure is indicated surrounding the armature *AB*, and also in the subdivision of the field windings *C* and *D* among the four poles. It must be noted that although, geometrically speaking there are four poles, magnetically considered, it is a bi-polar design. Similarly, as shown in Fig. 177, a three-phase bi-polar advancer

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has three geometric poles. The field windings are usually distributed in slots at the inner periphery of the stator instead of being arranged on salient poles as indicated diagrammatically in Fig. 176.

322. The Miles Walker phase advancer. In the phase advancer developed by Prof. Miles Walker, a compensating winding is added as shown in Fig. 178 in which $E_1E_2E_3$ are the three exciting windings and $C_1C_2C_3$ the three compensating windings. The exciting windings E are (for a bi-polar design) usually concentrated in three large equi-distant slots in the stator core, while the compensating windings C are distributed in many small slots in order to neutralize (or slightly overneutralize), the *m.m.f.* of the rotor winding. It is claimed for this type that it possesses features specially conducive to ready adjustment and good commutation.

323. Omission of stator windings in non-synchronous phase advancers. Leblanc's original proposals showed examples of phase advancers, in which no windings were provided on the stator. Such a plan as applied to a three-phase four-pole advancer, is shown diagrammatically in Fig. 179. The recesses opposite the brushes are provided for improving the commutation. Scherbius in some phase advancers built by Messrs.

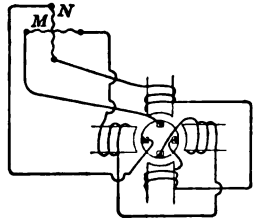


FIG. 176.



FIG. 177.

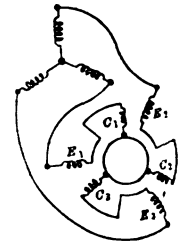


FIG. 178.

FIG. 176.—Alternative method of diagrammatic representation of Leblanc single-armature phase advancer.

FIG. 177.—Diagrammatic representation of phase advancer wound for three phases.

FIG. 178.—Miles Walker phase advancer with exciting and compensating windings on the stator.

Brown-Boveri & Co. has employed this plan of omitting exciting windings from the stator. But *compensating* windings are usually fitted on the stator in phase advancers for large slow-speed induction motors.

324. An understanding of the underlying idea of the non-synchronous phase advancer (Par. 321) may also be obtained by first considering that the low-frequency currents, from the secondary of the main motor, flow into the rotor of the phase advancer while it is at rest. Under these conditions the current will *lag*, since the rotor circuits are inductive. But if the rotor is driven in the direction of the magnetic field which is circulating in it and which has been occasioned by the *m.m.f.* of the low-frequency currents from the secondary of the main motor, and if the speed at which it is driven is exactly that of the rotating field, then there is a state of relative rest between the field and the rotor, and the latter's windings are non-inductive and occasion *neither lag nor lead*. If the rotor is driven at higher speeds, the rotor circuits again become inductive but introduce *leading* electromotive forces into the secondary circuits of the main motor.

325. Scherbius phase advancers with entire omission of stator. Scherbius has devised a phase advancer consisting simply in a rotor with its windings completely embedded below the surface. Diagrammatically such a phase advancer and its connections reduce to the simple arrangement shown in Fig. 180, in which A represents the rotor of the induction

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motor with its windings connected to the brushes of the Scherbius phase advancer B. The latter is usually mounted directly on the shaft of the main motor. Thus the scheme reduces to the simple proposition of establishing a field in the magnetic circuit of B by means of the *m.m.f.* of the current supplied to its brushes from A. This field rotates very slowly in space since the frequency of the rotor currents is small. But B is rotated mechanically at the high speed of the rotor A and consequently the windings on B rotate much faster than the magnetic field in B, and in cutting through this field they set up an e.m.f. which, combined with the e.m.f. in the main rotor, occasions an advance in the phase of the currents in the rotor circuits and improves the power-factor of the motor.

In a letter published in *The Electrician*, July 12, 1912, page 582, Scherbius states that both theory and practice support the idea that a mere ring is

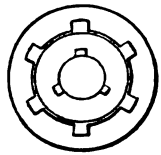


FIG. 179. — Leblanc-Scherbius phase advancer without windings on stator.

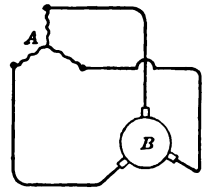


FIG. 180. — Diagrammatic representation of Scherbius statorless phase advancer.

sufficient to complete the magnetic circuit and that no stator is necessary. Consequently in a considerable number of his smaller sizes of phase advancers Scherbius has abandoned the use of a stator and has built his phase advancers without any air space in the magnetic circuit. The consequent reduction in the magnetic reluctance permits at small loads the generation of an increased e.m.f. of rotation and results in a greater improvement of the power-factor at light loads. See Ahmed, A. A., "Methods of Testing the Scherbius Compensator," *Jour.* I. E. E., Vol. 53 (1915), p. 640.

326. Operating data of Scherbius phase advancers. In Fig. 181 are given curves, showing the power-factor obtained by Scherbius on a

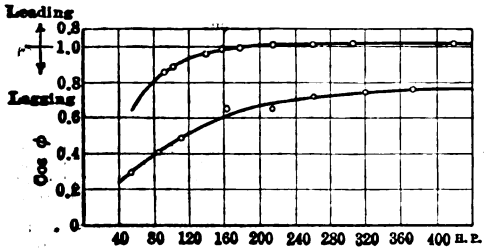


FIG. 181.—Performance curves of a 400-h.p. motor when operated respectively with (upper curve) and without (lower curve) a Scherbius phase advancer.

400-h.p. motor when operated respectively with and without a phase advancer. It is seen from the curves that at only 20 per cent. of rated load the power-factor is improved from 0.4 to 0.8, and that beyond half load the current is leading. The 400-h.p. motor on which the tests were made, has 24 poles and runs from a 3,300-volt, 32-cycle circuit at 160 rev. per min. The overall dimensions of the advancer (including a small motor to drive it) are 50 in. × 22 in. × 25 in., and the weight of the advancer and its driving

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motor amounts to 0.34 metric ton. This particular phase advancer was fitted with a stator but without any windings. The general tendency is toward the employment of a stator fitted with compensating windings but without any exciting windings. At page 366 of Vol. L, of the *Jour.* I. E. E. are given curves, reproduced in Fig. 182, showing the improvement effected in a 25-h.p., 50-cycle, 450-volt, 1,000-rev. per min., three-phase induction motor by fitting a Scherbius phase advancer on the end of the shaft of its rotor. In the motor the stator is the secondary and its three terminals are connected to three brushes on the commutator of the advancer. The total weight of the motor and advancer is only 0.36 metric ton, or 14.5 kg. per h.p.

At a steel mill in Sheffield in England, a Scherbius advancer with a stator fitted exclusively with compensating windings is employed in the rotor circuit of a 700-h.p. induction motor which is usually running lightly loaded. Without the phase advancer the power-factor of the system is 0.55. With the advancer it is increased to 0.7. The advancer is driven by a 2-h.p. induction motor running at nearly 1,500 rev. per min.

327. The Kapp vibrator. In *Eclairage Electrique*, for August 5, 1899, Leblanc suggested that phase control could be accomplished by the use of a device which he termed a "recuperator" and which consisted of a copper disc through which alternating current was transmitted radially between the centre and the periphery, and which was located in a magnetic

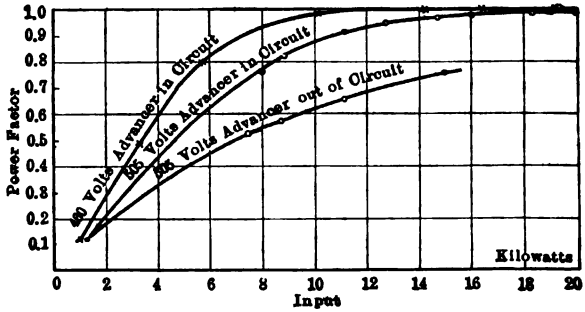


FIG. 182.—Performance curves of a 25-h.p. motor when operated respectively with and without a Scherbius phase advancer.

field in which it oscillated. The current was transmitted to and from the disc by means of a slip-ring on the shaft and a trough of mercury in which the disc dipped.

Dr. Gisbert Kapp has developed from this principle a commercial phase advancer which he terms a "vibrator." Kapp has realised that success is contingent upon employing as a vibrating element a rotor of small diameter. He conveys the current into the rotor windings by brushes bearing on a commutator. In order that the commutator may be small and cheap, it is desirable that the secondary of the main motor shall be wound for a fairly high pressure and small current. The scheme is illustrated in Fig. 183 taken from an article by Kapp published in *The Electrician* for May 17 and 24, 1912, pp. 222 to 272. *VVV* are three vibrating armatures for improving the power-factor of a three-phase motor whose rotor has a three-phase winding. A three-phase motor can, as well, have a two-phase rotor, and this will permit of reducing the number of vibrating armatures from three to two. A starting resistance, *S*, of the usual type is provided. It is short-circuited after the motor has acquired speed. The field of the vibrator is shown excited from a battery, but any convenient source of direct current may be employed. Dr. Kapp states that the power required for excitation is only a fraction of 1 per cent. of the power of the motor, and that the loss of power by windage and brush resistance in the armatures is of the same

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order of magnitude. A switch may be arranged to short-circuit the vibrator while the motor is being started and thus avoid subjecting the windings of the vibrating armatures to the high pressure established, during starting, in the rotor of the induction motor. When it is arranged to protect the vibrator in this way, its armature need only be provided with low-voltage insulation, since the pressure of the rotor windings during normal running is only a small percentage of the pressure during starting.

There is no difficulty in proportioning a vibrator for good commutation. At maximum speed the current is zero and at maximum current the speed is zero. Consequently at both these limits the reactance voltage is zero. The reactance voltage passes through its maximum value at some intermediate value of speed and current, but there is no difficulty in so proportioning the vibrator that this maximum value of the reactance voltage will be low. In Vol. I.I (1913) of the *Journ.* I. E. E., are given, p. 292 the curves reproduced in Fig. 184. These curves were obtained on a 40.8-cycle, 2,650 volt, 408-rev. per min., 12-pole, 90-h.p. induction motor, when run with and without a Kapp vibrator. The natural slip of the motor was 2.75 per cent. at full-load. The curves disclose a slightly undesirable feature which is more or less common to all these phase advancers, namely, that their use increases the slip. The use of a phase advancer, however, greatly increases the instantaneous overload capacity of the induction motor to which it is applied.

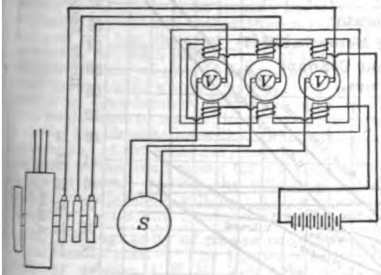


FIG. 183.—Diagrammatic representation of an induction motor and a Kapp vibrator type of phase advancer.

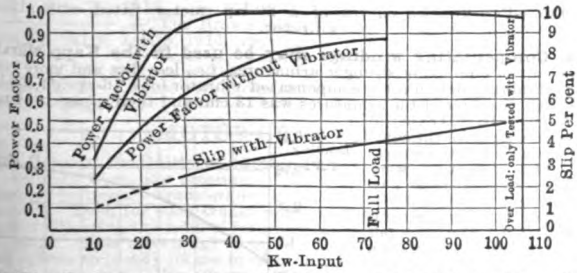


FIG. 184.—Performance curves of a 90-h.p. motor fitted with a Kapp vibrator.

328. Operating data of Kapp vibrator. In Fig. 185 are given curves showing the improvement effected in a 20-h.p. motor by equipping it with a Kapp vibrator. In Fig. 186 is given a power-factor curve obtained on a 200-h.p. 12-pole three-phase induction motor operated from a 40-cycle, 2,750-volt circuit and fitted with a Kapp vibrator. In this case the armatures of the vibrator are only 10 cm. in diameter and at full-load, with a slip of 2.45 per cent. rotate about 3½ revolutions in each direction. Since the frequency of supply is 40 cycles per sec., the direction of rotation reverses every half second. The curve shows that at half load the power-factor was 0.99 leading; and that at full-load it was 0.96 leading. The corresponding power-

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factors without the vibrator, were 0.76 lagging and 0.87 lagging respectively. The excitation loss in the fields of the vibrator was only 50 watts.

The Kapp vibrator's chief advantage over revolving types of phase advancers relates to the greater facility with which good commutation may be obtained. A disadvantage relates to its dependence upon a supply of direct current for field excitation.

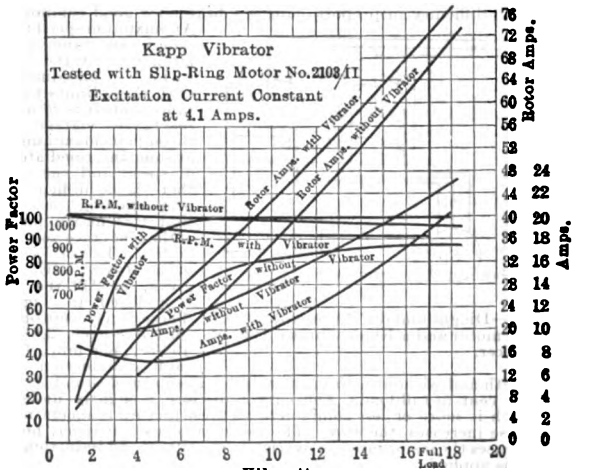


FIG. 185.—Performance curves of a 20-h.p. motor fitted with a Kapp vibrator.

329. Compensating windings may be used in the Kapp vibrator and permit of employing stronger armatures, *i.e.*, less flux and more turns. In a preliminary design for a compensated vibrator for a 16-cycle 1,500-h.p. motor, the diameter of the armatures was 13 cm. and their gross core length was 15 cm. In this case the estimated weight for the complete vibrator was 0.5 metric ton. The armatures were calculated to make some 7 to 8 revolutions in each direction and to attain a peripheral speed of about 30 meters per sec. In another design for a vibrator for a 350-h.p., 50-cycle induction motor, the diameter of the vibrator's armatures was 12 cm., and the gross core length was 24 cm. This could be considered as a case in which the conditions were favorable, for the natural slip of the motor was only 1.5 per cent. at rated load and the slip-ring pressure was high, namely, 600 volts. The weight of this vibrator was estimated at 0.55 metric ton, and the calculations indicated that the power-factor would reach 1.00 at one-fourth load, and that there would be a leading current from one-fourth load up to heavy overloads.

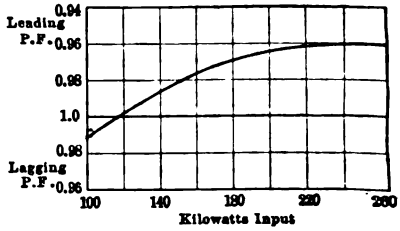


FIG. 186.—Power-factor curve of a 330-h.p. induction motor fitted with a Kapp vibrator.

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335. Synchronous-motor drive for motor-generator sets. The use of a synchronous motor-generator for transforming from alternating to direct current permits of effecting phase control to practically any desired extent; whereas, with a synchronous converter, phase control is only practicable within very narrow limits (Sec. 9). Moreover the direct-current generator of a motor-generator set can be provided with all the desirable attributes of a machine driven by a prime mover. Although the motor-generator set may be employed in a substation many miles away from the generating station, the direct-current generator will have as close speed regulation as the prime movers in the generating station. Its voltage may be controlled through any desired range and it may be provided with a compound winding for giving it practically any characteristics which may be desired. For operating from 60-cycle circuits and for commutator pressures above 1,200 volts, the synchronous converter has a competitor in the synchronous motor-generator set. The motor converter (Sec. 9) is also a rival for such work. For still higher commutator pressures, the synchronous motor-generator set is exclusively suitable for operation from 60-cycle circuits and it is often preferable on 25-cycle circuits.

336. Induction-motor drive for motor-generator sets. While it is usually preferable to employ a synchronous motor for a motor-generator set, cases arise where the simplicity of the squirrel-cage induction motor and its lower cost is considered sufficient inducement to employ it notwithstanding its low power-factor and its slip. The induction-motor drive is usually confined to relatively small sets and for low voltages at the motor. It is less objectionable at 25 than at 60 cycles, since for a given size and speed the power-factor of induction motors is higher the lower the periodicity.

337. Starting of motor-generator sets. It is at present usual to start synchronous motor-generator sets from low-voltage taps of transformers or auto-transformers by means of the torque supplied by squirrel-cage windings fitted in the pole shoes. After the rotor has come up to speed, the stator windings are thrown over to the full-voltage position. The method differs in no essential respect from the "tap" starting of any synchronous motor or rotary converter. Another available method which as yet is but rarely employed in America consists in fitting a small auxiliary induction motor on the shaft with its stator windings either in series with the stator windings of the synchronous motor or else with its stator windings supplied from the secondaries of a series transformer whose primaries are, during starting, in series with the synchronous motor's stator windings. This method is especially appropriate for large sets and is widely used in England. The rotor often consists of a cast-iron cylinder without any slots or windings. As a third method may be mentioned that of starting from the commutator end by temporarily employing the direct-current generator as a motor. Some 25 per cent. of rated full-load current is usually required by this method of starting motor-generator sets. The method is the more worthy of consideration, the higher the frequency of the supply circuit, since tap starting requires more current with the higher frequencies. If the set is started from the commutator end, the compound winding should be temporarily short-circuited by a switch mounted on the frame of the machine or close to it. For this method of starting it becomes necessary to employ synchronizing apparatus. When induction motor-generator sets are employed, one of the motives usually relates to the readiness of starting from the induction-motor end in the same way in which any large squirrel-cage induction motor is usually started up, *i.e.*, by taps from transformers or induction starters.

338. Motor-generator sets for charging storage batteries. It might be concluded at first sight that the mercury-arc rectifier would monopolise the function of charging storage batteries when the available supply consists of alternating current. There is, however, a consideration which often weighs decidedly in favor of the motor generator for such work: There is an internal drop of some 20 to 30 volts in the mercury arc rectifier. Let us for explanatory purposes take the drop as 25 volts. Then for supplying electricity at a pressure of 25 volts, the efficiency cannot be greater than $[25/(25+25)]\times 100 = 50$ per cent. But for supplying energy at 250 volts, the efficiency may be of the order of $250/(250+25) = 91$ per cent.

Consequently the higher the required pressure the more appropriate is

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the mercury-arc rectifier, and the lower the required pressure the more appropriate is the motor-generator. We thus see that for low-voltage storage-battery charging there is an important consideration weighing in favor of the motor generator, although its greater initial cost, the greater cost for attendance, and the general inconvenience inherent to rotating machinery may turn the balance in favor of the mercury-arc rectifier in many instances.

339. Motor-generator sets for electrolytic work. The explanations in Par. **338** apply in still greater degree to the provision of direct-current for such electrolytic work as requires a pressure of only a few volts. For such work the required pressure is often of the order of only some 2 to 10 volts. Since the technical problems arising in connection with such sets hinge around the abnormal proportions required for the direct-current generator, and since the alternating-current motor for such sets is entirely normal, this matter is more appropriately discussed in Sec. 8.

340. Motor-generators for main-line railway substations. In most main-line railway electrification, direct current will be suplied to the conductor rail or overhead trolley wire at pressures of not less than 1,200 volts and often of from 2,400 volts, to 4,000 volts. Such pressures cannot successfully be provided by synchronous converters or motor converters. Consequently motor-generators will be employed.

341. Ward Leonard system. The modern conception associated with the term "Ward Leonard System" is of a system for effecting any desired variations in the speed of a motor for all loads carried by the motor without incurring any rheostatic losses in the main circuit. This is accomplished by interposing a motor-generator set between the variable-speed motor in question and the system from which it is supplied. If the system be one furnishing alternating electricity it will be usual to employ for the motor-generator set a synchronous motor coupled to a direct-current generator. It is arranged that the excitation of the latter may be varied over a wide range by means of a rheostat in its field circuit. The generator's armature and the motor's armature consitute a circuit by themselves which is not interrupted in service. By simple and efficient manipulations of the field rheostats and switch gear in the exciting circuits of the generator, and of the variable-speed motor the latter's speed and direction of rotation are under perfect control at all loads. The system is regenerative; thus, when applied to hoisting, the descending load drives the motor, which, as a generator, reverses the action of the motor-generator set and returns energy to the supply system.

342. The Ward Leonard system has been applied to a large variety of work requiring economical operation under widely varying conditions of speed and load. Among these applications that of operating railway trains is of interest. In this instance Ward Leonard employed single-phase transmission to a motor-generator set on the locomotive. The generator delivered direct current to motors geared to the driven axles. The control was effected exclusively by manipulation of the field excitation. This system of railway electrification was formerly occasionally employed by the Oerlikon Co.

343. Bibliography of Ward Leonard system. The system has been described and discussed on several occasions when its inventor presented papers before the American Institute of Electrical Engineers. The following is a list of several papers by H. Ward Leonard relating to his system; these were published, at the various times noted, in the *Trans.* A. I. E. E.

"A New System of Electric Propulsion (June, 1892)," Vol. IX, page 566.

"How Shall We Operate an Electric Railway Extending One Hundred Miles from the Power Station" (Feb., 1894), Vol. XI, page 76.

"Volts vs Ohms (Speed Regulation of Electric Motors)" (Nov., 1896), Vol. XIII, page 377.

"Multiple Unit, Voltage-speed Control for Trunk Line Service" (Nov., 1902), Vol. XX, page 155.

344. The Ilgner system. By providing the motor-generator set with a fly-wheel, Ilgner goes a step farther than Ward Leonard and obtains a system for supplying electricity to a motor which shall carry sharply varying loads at widely varying speeds without imposing any material load variations on the supply system. When operated from a direct-current supply, both

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members of the motor-generator set are direct-current machines as indicated at *A* and *B* in Fig. 187. The shunt motor *A* is supplied from the direct-current system *G*, and drives the generator *B* and the fly-wheel *C*. It is desired that the motor, *F*, shall be economically operated at any speed in either direction and with widely varying loads. For instance, *F* may drive reversible rolls in a steel mill or a winder at a coal mine. (Although in the case of such heavy work, the supply would consist in polyphase electricity, it is simpler first to describe the arrangement employed with a supply of continuous electricity.) It will be observed that there are no switches or rheostats in the circuit of the armatures of the generator *B*, and the variable-speed motor *F*. The excitation for the latter may be supplied from *G*, as indicated in the diagram. The control of the speed of *F* is effected by control of the field excitation of the generator *B* by means of the rheostat *D*. The direction of *F* is controlled by the switch *E*. Assuming the case of winding a load up out of a shaft, let us take the moment when the load is at rest at the bottom. Switch *E* will be open at this moment and *F* will be at rest. To wind up the load the switch *E* is closed in the right direction and the field of *B* is rapidly strengthened by cutting out the rheostat *D*, point by point. This accelerates the motor *F* to its full speed.

The load thus imposed on the fly-wheel motor-generator set is largely provided from the energy stored up in the fly-wheel *C*. By the time the wind is completed, the motor generator's speed has decreased a few per cent. During the descent, the motor *A* is still loaded, since it is accelerating the fly-wheel to its full speed and storing energy in it. The descending load may contribute to the process by regeneration.

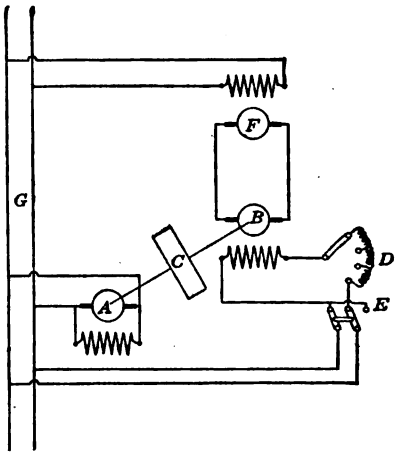


FIG. 187.—Ilgner system.

345. Field of application of the Ilgner system. The Ilgner system has been extensively used and instances are on record of reversing rolling mills in which load variations of enormous amount occurring many times per min. are so effectively equalized as to occasion practically constant load on the supply system. See Sec. 15. However, for heavy work of this character, the supply consists of polyphase energy, and an induction motor replaces the direct-current motor *A* of the motor-generator set. But the generator *B* and the variable-speed motor *F* remain direct-current motors, and the operation is quite as explained above. It is, however, necessary to provide an exciter for the field winding of *F*. Furthermore, certain details are introduced relating to the automatic insertion of resistance in the secondary windings of the induction motor of the motor generator, in order to control the rate and extent of delivery of the kinetic energy of the fly-wheel.

FREQUENCY CHANGERS

346. Field of application of the frequency changer. With the rapidly extending employment of electricity as a means of transmitting energy to a distance, it has come about that most civilized regions of the world are now provided with enormous networks of transmission conductors. Various networks in neighboring localities are often the outgrowth of small undertakings which were originally in competition with one another, and they differ as regards pressure, phase system, and frequency. At the present

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stage of development it is becoming important to interconnect these systems. The difference in pressure and phase system are readily reconciled by means of stationary transformers, Sec. 6. But the different *frequencies* can only be dealt with commercially in the linking-up process by means of rotating machinery termed "frequency changers." Such machines are also required when, for a portion of the load on a system, a different frequency is appropriate from that required for the bulk of the load. Thus single-phase railways are less unsatisfactory the lower the frequency employed. Consequently when a large 60-cycle power-supply undertaking contracts to supply a single-phase railway, frequency changers must be employed to provide electricity of a frequency of 25 or preferably 15 cycles per sec. In Europe a periodicity of 16.66 cycles per sec. has been standardized for single-phase railways, and 50 cycles for general power and lighting purposes. Without devoting more space to a specific discussion of the occasions for frequency changers, we may briefly subdivide these occasions into two groups relating, respectively: first, to the case of the exclusive supply of electricity through a subsidiary system with no other source of power, at a frequency differing from that of the main system, and, secondly, to the linking up of two systems of different frequencies, each system also having its own independent generating plant. While the first case is relatively simple, a number of important considerations involving attention to complex details arise in connection with the second case.

347. Frequency changers for the exclusive supply of subsidiary networks. Let us now deal with the first case and base our explanations on the example of a circuit for which 25-cycle energy is required, the frequency of the main system being 60-cycles. The simplest plan, and the one almost always adopted, consists in employing a synchronous motor-generator set, the motor of which is designed to run at 60-cycles while the generator is designed with such a number of poles that, when driven by the motor, its frequency will be 25 cycles per sec. The smallest number of poles for these two combinations are 24 for the motor and 10 for the generator, since $24/2 = 12$, and $10/2 = 5$ are the smallest whole numbers bearing to one another the ratio of 60 to 25. A 24-pole motor on a 60-cycle circuit runs at $(60 \times 60)/12 = 300$ rev. per min. It is usually desirable to select the smallest practicable number of poles, since this corresponds to the highest speed and consequently to the smallest and cheapest motor-generator set. The synchronous motor of such a set may be designed with an appropriate squirrel-cage (amortisseur) pole-face winding to enable it to run up to speed as an induction motor. In this case it will be started from low-pressure taps of a transformer or induction starter as described in Par. **337**. As an alternative, it may be started by means of an induction motor in series as also mentioned in Par. **337**, and will be self-synchronizing. In other instances it may be preferred to employ an auxiliary direct-current motor to bring the set up to speed. After the set is in synchronism, the 25-cycle load may be supplied from the generator. Synchronous frequency changers have the good feature that by overexciting the synchronous motors, they can be made to also act as synchronous condensers to improve the power-factor of the system as described in Par. **319** and **320**.

348. Induction motor versus synchronous motor as primary member of a frequency changer set. Except for this last feature (Par. **347**), it may occasionally be preferable in such a case to employ a motor of the non-synchronous type and with a squirrel-cage rotor. But by such a plan a lagging load will be imposed upon the main system and this will usually be so objectionable that it will more than offset the advantage of simplicity possessed by the squirrel-cage induction motor. Furthermore, it will not permit us to dispense with a supply of direct-current for excitation, since this will be required in any case for providing the excitation for the generator member of the motor-generator set. In exceptional cases it might be a good plan to let the motor be of the induction type and arrange to operate it at unity or leading power-factor by the employment of a phase advancer of one of the types discussed in Par. **321** to **331**. The Brooklyn Edison Co. has 1,000-kw. and 500-kw. induction-motor-driven frequency-changer sets (which have been supplied by different manufacturers) operating in parallel.

349. The parallel operation of two or more frequency changers. If two or more frequency changers of the synchronous motor-generator type mentioned in Par. **333** and **347** are required to operate in parallel in

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supplying a load, certain complications arise due to the necessity for synchronising the frequency changers at both ends, and due to the requirement that the internal reactance and shifting of magnetic axes in the machines (with loads varying as regards amount or phase) shall not be such as to cause inappropriate division of the load among the different machines in parallel. These matters have been carefully considered by J. B. Taylor in a paper entitled "Some Features Affecting the Parallel Operation of Synchronous Motor-generator Sets," published in Proceedings of the American Institute Electrical Engineers, Vol. XXV (1906), p. 113 and by N. E. Funk in a paper entitled "Operation of Frequency Changers" at p. 1579 of the July, 1913, issue of the Proceedings American Institute Electrical Engineers. The relations involved are too complicated to be satisfactorily abstracted. Let us, however, consider the matter briefly by reference to the case of supplying 40 cycles from a 60-cycle system through two sets, each consisting of a 6-pole 1,200-rev. per min. synchronous motor, direct-connected to a 4-pole synchronous generator. Let us assume that the relative angular positions of the generator and motor fields are as shown in Fig. 188, see *I* and *II*. Set *I* is in service and it is desired to place set *II* in parallel with it. The large letters *N* and *S* relate to the North and South poles of the 6-pole motors and the small letters *n* and *s* to the poles of the 4-pole generators. It is not only necessary that the North poles of the motors of *II* shall occupy the same angular positions as the North poles of the motors of *I*, but it is furthermore

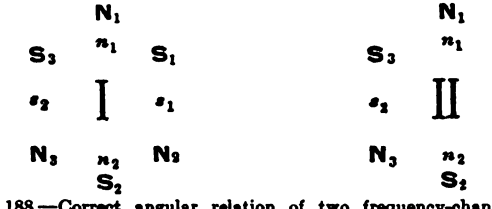


FIG. 188.—Correct angular relation of two frequency-changer sets for parallel operation.

necessary that a particular North pole N_1 of *II* shall occupy the same angular position as a particular North pole N_1 of *I*. It is not permissible that N_2 or N_3 of *II* shall be synchronized with N_1 of *I*, since then a North pole of the *generator* of set *II* could not be brought into the same angular position as a North pole of the *generator* of set *I*.

350. Synchronising unloaded frequency changers. Thus, when synchronising at random, there is only one chance in three that the desired relative positions will be obtained. Consequently after synchronising the two motors, the fields of one of them will usually have to be reversed either once or twice, before the correct relative positions of the two generator fields is obtained.

351. Synchronising loaded frequency changers. If, when it is desired to add set *II* to the system, set *I* is, as will usually be the case, already loaded, then the *magnetic* axes in set *I* will be displaced from the *geometric* axes and this displacement will not be exclusively a function of the amount of the load but will also be greatly dependent upon whether it is in phase or whether and to what extent it is lagging or leading. The matter is increased in complexity when frequency-changer sets of different designs and capacities are to be operated in parallel. When care has not been exercised in the original designs, it has often proved impossible to arrange to divide the load in proper proportions between the different sets. One set may take too great a share at light loads and too small a share at heavy loads, or one set may take too great or too small a share at all loads. All these troubles may be avoided by the application of known principles, but there have in the past been many instances in which factors requiring careful attention have been overlooked. Funk in the paper to which

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reference has already been made, describes interesting arrangements for synchronising frequency-changer sets when operating in parallel.

353. Refinements of construction necessary to permit of parallel operation. From the above discussion it will be evident that in order to obtain an appropriate division of the load between two frequency changer sets operated in parallel, great exactness in construction and adjustments is necessary. It is desirable to be able to effect a final mechanical adjustment of the stators with relation to one another. This is often arranged by providing a cradle construction. The stator of one machine is bolted to a cradle fastened to the base. By "slacking off" the bolts, a small angular adjustment of the stator may be effected, and the bolts afterward tightened.

354. Efficiency of a motor-generator frequency changer. By using a motor-generator set as a frequency changer, each of the two machines has to be proportioned for the entire load to be delivered to the changed-frequency circuit, and the set is consequently large and expensive. Furthermore, if each machine has an efficiency of, say, 95 per cent., the combined efficiency is only 91 per cent. since $0.95 \times 0.95 = 0.91$.

355. Induction-type frequency changer. We shall now consider means by which better results, in these respects, may sometimes be obtained. These means rest fundamentally upon the circumstance that, in an ordinary polyphase induction motor, the frequency of the current in the rotor winding depends upon the speed of the rotor. Let us consider a 60-cycle three-phase induction motor with a three-phase rotor and three slip-rings. If the stator windings are connected to a 60-cycle circuit, then if the rotor is restrained from moving, the frequency in the rotor windings will also be 60-cycles per sec. If, on the contrary, the rotor's speed is the same as that of the revolving magnetic field in the stator, and in the same direction, then the frequency in the rotor winding will be zero. Thus if the 60-cycle induction motor has four poles, the magnetic field will travel around the stator at a speed of: $(60 \times 60) \div (4/2) = 1{,}800$ rev. per min.

If the rotor's speed is also 1,800-rev. per min. and in the same direction, then the frequency in the rotor windings will be zero. If, however, the rotor's speed is only 1,200 rev. per min. the frequency will be $[(1{,}800 - 1{,}200)/1{,}800] \times 60 = 20$ cycles per sec. If the rotor's speed is only 300 rev. per min., the frequency will be $[(1{,}800 - 300)/1{,}800] \times 60 = 50$ cycles per sec. If the rotor is restrained from running, the frequency will be $[(1{,}800 - 0)/1{,}800] \times 60 = 60$ cycles per sec. If the rotor is driven at a speed of 300 rev. per min. in a direction opposite to that of the magnetic field in the stator, the frequency will be $[(1{,}800 + 300)/1{,}800] \times 60 = 70$ cycles per sec.

In our case we wish a frequency of 25 cycles per sec. Consequently, if we denote by R the speed at which we shall drive the rotor we may have either $[(R - 1{,}800)/1{,}800] \times 60 = 25$ or $[(1{,}800 - R)/1{,}800] \times 60 = 25$ and $R = 2{,}550$ or $R = 1{,}050$.

356. Direct-current motor drive for induction-type frequency changer. Let us select the former case and drive the rotor at a speed of 2,550 rev. per min., by another motor. We can only do this if we have a source of supply of continuous electricity and employ a 2,550 rev. per min., continuous-electricity motor. We could not employ a 60-cycle induction motor to drive the rotor since this would run at only 1,800 rev. per min., if wound with 4 poles and at 3,600 rev. per min., if wound with 2 poles, and we require it to run at 2,550 rev. per min.

357. Alternating-current motor drive for induction-type frequency changers. If there is no source of continuous electricity supply, thus limiting us to the use of a 60-cycle motor to drive the rotor of the frequency changer, then we shall have to abandon the plan of employing a 4-pole frequency changer and we shall be obliged to employ one with more poles which, consequently, will be heavier and more expensive. We can determine upon a suitable combination by consulting the table in Par. **357.**

357. Selection of proper speed and number of poles in induction-type frequency changers. In the table given in Par. **358**, the smallest number of poles which, in column *IV*, corresponds to the synchronous speed of 60-cycle motor, is 14, corresponding to a rotor speed of 300-rev. per min. A frequency changing outfit thus consists of a 14-pole induction motor with its rotor driven by a 300-rev. per min., 60-cycle synchronous motor which will, consequently, have $2 \times [(60 \times 60)/300] = 24$ poles. But, for so

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slow a speed, the outfit will be heavy and expensive. Examining colum *V* of the table we see that for an 8-pole frequency changer in which the rot is driven at a speed greater than that of the stator field, the required spe is 1,275 rev. per min. Since a 6-pole, 60-cycle synchronous motor runs at speed of only 1,200 rev. per min., the frequency will be only (1,200/1,275) 25 = 23.5 cycles per sec.

It has been assumed that the frequency changer is required for supplyi an independent circuit which has no other source of supply. In such a case, periodicity of 23.5 cycles would usually be nearly as appropriate as 25 cycl If, on the other hand, we were to elect to employ a 6-pole frequency chang the rotor speed required for 25 cycles would, as seen from column *V*, 1,700 rev. per min., and if we arranged to drive it by a 4-pole synchrono motor, the speed would be 1,800 rev. per min., giving (1,800/1,700) × 25 26.5 cycles per sec. If, in the latter case, we were to employ a squirr cage induction motor to drive the rotor, instead of employing a synchrono motor, and if we were to design the induction motor for a full-load slip 5.5 per cent., then the periodicity would vary from 26.5 cycles, at no-loa to 26.5 × 0.945 = 25.0-cycles, at full-load. Enough has been said to indica that the circumstances of each proposed installation will largely govern t suitable design.

358. Table of relative speeds for induction-type frequency changers

Number of poles of stator of frequency changer	Speed of magnetic field in stator when excited from 60-cycle circuit	Required relative speed of stator field and rotor in order to provide 25 cycles in rotor	Speed at which rotor must be driven	
			Rev. per min.	
			If below speed of stator field	If above spee of stator fiel
I	*II*	*III*	*IV*	*V*
2	3,600	1,500	2,100	5,100
4	1,800	750	1,050	2,550
6	1,200	500	700	1,700
8	900	375	525	1,275
10	720	300	420	1,020
12	600	250	350	850
14	514	214	300	728
16	450	187.5	262.5	637.5
18	400	166.7	233.3	566.7
20	360	150.0	210.0	510.0
22	327	136.5	190.5	463.5
24	300	125.0	175.0	425.0
26	277	115.3	161.7	392.3
28	257	107.0	150.0	364

359. A disadvantage of induction-type frequency changers relat to the need for delivering energy to the system from the slip-rings of t rotor. This limits the voltage which can be supplied to the low val for which it is expedient to wind a rotating element, and may entail t necessity for a step-up compensator or transformer. The outfit also r quires the inclusion of some form of potential regulator to provide the pr cise voltage required at all loads.

360. Power required to drive the rotor of an induction-type fr quency changer. In induction types of frequency changer, irrespecti of whether the rotor is driven by a direct-current motor, a synchronous mot or an induction motor, the output required of the motor driving the ro will (if the rotor is driven in the same direction as the stator field) be equal the output from the frequency changer plus the copper losses in the latte rotor circuits. If, on the contrary, the rotor is driven in opposition to t stator field, the output required from the driving motor is only proportio to that part of the frequency which it adds to the frequency impressed by t main circuit. For example, if 60-cycles is required from a 50-cycle circu

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may employ a 4-pole frequency changer and drive its rotor at 300 rev. r min. in opposition to the 1,500 rev. per min. of the stator field. If the tput delivered from the frequency changer is 1,000 kw., then $(300/1,800) \times$ $00 = 167$ kw. is provided by the driving motor and $(1,500/1,800) \times 1,000 =$ 3 kw. is provided by the frequency changer itself in its transformer pacity, and at high efficiency.

Obviously the less the required alteration in frequency, the greater is e appropriateness of the induction-type of frequency changer as compared th the motor-generator type.

361. Relative merits of various kinds of motors for driving the tor of an induction-type frequency changer. Whether or no it ay be practicable to employ an induction motor to drive the rotor, depends a considerable extent upon the importance or otherwise of supplying solutely constant frequency at all loads. When it is permissible that the quency may decrease 1 or 2 per cent. or more from no-load to full-load, induction motor may provide the most satisfactory solution, since it minates the necessity for having a supply of continuous electricity for itation.

In some instances instead of employing a squirrel-cage induction motor d then having a slip necessarily proportional to the load, it becomes propriate to drive the frequency changer's rotor by a slip-ring induction tor and regulate its slip, and consequently the frequency supplied, by ulating the resistance in its rotor circuits. This becomes the more expedi- , the smaller the proportion of the total energy which is supplied by the ving motor. For instance, in the example in Par. **360**, only $(300/1,800) \times$ $) = 16.7$ per cent. of the total output, is provided by the driving motor, d a considerable rheostatic loss in its rotor circuits would not seriously ect the efficiency of the complete outfit. It should again be emphasized at induction-type frequency changers are not used in commercial practice. chronous motor-generator sets are practically always employed.

362. Frequency changers for connecting two systems, each of ich has its own generating machinery of fixed frequency. We e come to the problem encountered when frequency changers are employed ween two systems each of which has a definite frequency imposed upon it its own generating plant. Synchronous motor-generator sets have rly always been employed for this class of work. Thus, in order to link two systems with frequencies of 60 and 25 cycles per sec., respectively, two chronous machines of 24 and 10 poles respectively are coupled together. s necessary for the frequencies of the two systems to be exactly identical order to successfully operate such plant. Furthermore, there are the ious complicated relations necessarily observed in synchronizing such paratus, as already discussed in Par. **349**.

ndeed, there is the further consideration that when **sets for parallel ration** are so proportioned and adjusted that they share the load in ap- priate proportions when delivering power from, let us say, a 25-cycle tem to a 60-cycle system, the division of the load will be altered when it is ired to reverse the sets and deliver power from the 60-cycle set to the -cycle system. Notwithstanding the niceties imposed by the relative- quency conditions, synchronous motor-generator sets constitute the al means employed.

When synchronous sets are employed to link two large systems, the htest alteration in the relative frequencies of the two systems occasions rmous fluctuations in the load carried by the frequency changers. This iculty is less the greater the size of the frequency changers as compared h the size of the systems connected. Unless the frequency changers are arge size as compared with the size of the systems which they connect, y will be pulled out of step if there is any slight change in the ratio of the quencies of the two systems. Consequently, when the frequency changers not be of relatively great size, it would be preferable to employ sets in ich an induction machine constitutes the motor member.

363. Induction-motor drive for non-reversible frequency changers. ere the object is to deliver energy always in the same direction, the em- yment of an induction machine with a slip-ring rotor as motor element, l the control of its precise speed by the adjustment of a rheostat in its or circuits provides freedom from the necessity for maintaining at exactly same value the ratio of the frequencies of the inter-connected systems.

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Indeed any slight change in the ratio of the frequencies is automatically accompanied by an appropriate alteration in the slip of the induction motor and this alteration is of such a nature as to reduce the accompanying load variation to a moderate amount.

364. The use of an induction machine in a reversible frequency changer. It has even been suggested that by the adoption of suitable pole numbers and by providing sufficient range of slip-control by the resistances in the rotor circuits, such a set could be employed reversibly. In such a case the induction machine would function as a generator to an extent which may be controlled by adjustment of the resistances in the rotor circuits.

365. Frequency changing by two induction machines. Both machines could be of the induction type, the one operating as a motor and the other as a generator. This arrangement, if required to be reversible, would, however, only be possible for connecting two systems each of which is provided with synchronous apparatus, since the generator member would be dependent upon such apparatus for its excitation. Each machine would have a slip-ring rotor and the amount and direction of the load would be controlled by adjustment of the amount of resistance in the rotor circuits.

366. Position of shaft in frequency changers (horizontal or vertical). While frequency changers are usually built with horizontal shafts, the vertical type offers the advantage in large sets that an economy in floor space is effected. The construction may also permit of reduced friction losses.

367. Number of bearings in frequency changers. Where floor space is restricted, sets with only two bearings are occasionally employed. Three-bearing designs are, however, to be preferred. They afford better opportunity for circulation of air through the machine, since the shaft may be smaller. Such designs also provide for more ready access to all parts.

368. Pairs of rotary converters as frequency changers. It has been proposed to accomplish frequency transformation by the employment of two rotary converters arranged with their alternating-current ends connected to the circuits of the two frequencies and with the commutators in parallel. This plan of transforming from alternating electricity of one frequency into continuous electricity and then into alternating electricity of another frequency avoids the difficulties of speed inflexibility of synchronous motor generators while retaining their desirable feature as regards power-factor control.

369. Literature relating to frequency changers is rather meagre. The most important contributions are: J. B. Taylor's paper entitled, "Some Features Affecting the Parallel Operation of Synchronous Motor-generator Sets," Proc. A. I. E. E., Vol. XXV (1906), p. 113, N. E. Funk's paper entitled, "Operation of Frequency Changers," Proc. A. I. E. E., July, 1913, p. 1579, and R. Townend's paper entitled "Frequency Changers," *Journ.* I. E. E. (1917), Vol. 55, p. 197.

In the *Electrician*, Sept. 27, 1912, page 1021, is an article by C. Turnbull, entitled, "Frequency Changers." In the *General Electric Review*, August, 1913, page 609, are some notes on "Frequency-changer Sets." In the *General Electric Review*, Dec., 1913, page 941, is an excellent article by Gordon Harris and L. B. Bonnett entitled, "Frequency Changers," which covers the main considerations thoroughly. See also "Parallel Operation of Frequency Changers," by G. H. Rettew at p. 836 of *Gen. Elec. Review* for August, 1915.

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SECTION 8

DIRECT-CURRENT GENERATORS AND MOTORS

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SECTION 8

DIRECT-CURRENT GENERATORS AND MOTORS

GENERAL PRINCIPLES

1. Lines of magnetic flux. A magnetic field may be represented b continuous lines, called lines of flux, whose direction at any point in the fiel is that of the force acting on a north pole placed at the given point; the therefore emerge from a north pole and enter a south pole (Sec. 2).

2. Electromagnetic induction. When the total magnetic flux threac ing a coil undergoes a change, an electromotive force (e.m.f.) is generate or induced in the coil. This e.m.f. is proportional to the time rate of chang of flux. One volt is generated in a coil of one turn when the rate of chang of flux threading the coil is 10^8 lines per sec.

3. Magnitude of induced e.m.f. In Fig. 1, N and S are respectively th north and south poles of a magnet and ϕ represents the direction of th magnetic flux passing from the north to the sout pole. When coil A is moved from position 1 wher the flux threading the coil is ϕ, to position 2 wher the flux threading the coil is zero, in t sec., the averag e.m.f. generated in the coil is $E = (\phi/t)\ 10^{-8}$ volts.

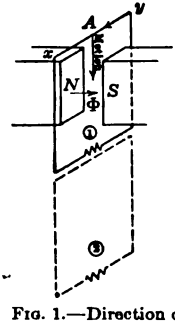


FIG. 1.—Direction of generated e.m.f.

4. The direction of the generated e.m.f. may b found by **Fleming's right-hand rule**, which state that if the thumb, forefinger, and middle finger of th right hand be placed at right angles to one anothe so as to represent three coordinates in space, with th thumb pointed in the direction of motion of the con ductor relative to the field, and the forefinger in th direction of the lines of flux, then the middle finge will point in the direction of the induced e.m.f (Sec. 2). The direction of the e.m.f., found b Fleming's rule, is shown by the arrow in Fig. 1 and it may be seen (Sec. 2), that the magneti effect of the current produced tends to preven the flux threading the coil from decreasing or, a stated by Lenz's law (Sec. 2), the generated e.m.f always tends to send an electric current in such direction as to oppose the change of flux which pro duces it.

5. Force on a conductor in a magnetic field. A conductor L cm long, carrying a current of I amp. perpendicular to a magnetic field of $\mathfrak{G}$ lines per sq. cm., is acted on by a force of $\mathfrak{G}LI/10$ dynes in a direction found by **Fleming's left-hand rule**, which states that if the thumb, the forefinge and the middle finger of the left hand be placed at right angles to one anothe so as to represent three coordinates in space, with the thumb pointed in th direction of the force on the conductor and the forefinger in the direction o the lines of flux, then the middle finger will point in the direction of th current.

6. Identity of generator and motor structure. Diagram A, Fig. 1 shows a generator under load; the direction of rotation is determined by th prime mover, while the direction of the current in the conductors may b found by the right-hand rule (Par. 4). A force is exerted on the con ductors, inasmuch as they are carrying current in a magnetic field; th direction of this force is found by the left-hand rule (Par. 5) and is opposed t

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e.m.f. is being generated in it, that is, it should be midway between the poles or in the neutral position.

9. Field excitation. The m.m.f. necessary to establish the flux in the magnetic circuit is obtained by means of field coils which are wound upon the poles of the machine. The exciting current for the field coils may be supplied in various ways. When a generator supplies its own exciting current it is said to be **self-excited**; when the exciting current is supplied from some external source, such as an exciter, the machine is said to be **separately excited**. The different connections used are shown diagrammatically in Fig. 4.

Diagram *A* shows a separately excited machine. Diagram *B* shows a **shunt machine**, in which the field coils form a shunt across the armature terminals and have many turns of small wire carrying a current which is proportional to the terminal voltage of the machine. This field current seldom exceeds 5 per cent. of the armature current under full-load conditions. Diagram *C* shows a **series machine**, in which the field coils are in series with the

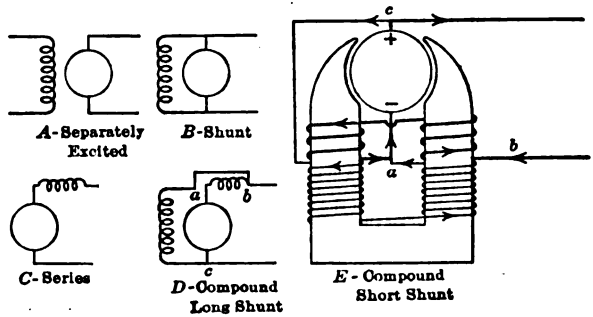


FIG. 4.—Methods of excitation.

armature and have fewer turns than the coils of a shunt winding, but employ a larger size of wire because they carry the whole or a fixed proportion of the total current. Diagram *D* shows a **compound machine** in which there is connected to the terminals a shunt winding which carries an exciting current proportional to the terminal voltage; and also a series winding which carries a current proportional to the armature current. This method of connection is known as the "**long shunt.**" Diagram *E* shows a compound machine connected in another manner. The connection in this case is known as the "**short shunt**"; that is, the shunt coil is connected to the terminals of the armature. Small machines using permanent magnets for field poles are called **magnetos.**

CLASSIFICATION OF TYPES

10. Classification according to the number of poles, as follows:

(a) **Bipolar machines** (Fig. 4) have only two poles.

(b) **Multipolar machines** (Fig. 46) have more than two poles; the number of poles is always a multiple of two.

(c) **Homopolar machines** (Fig. 89) have two poles, but the conductors always cut lines of unidirectional flux. The resulting e.m.f. is continuous in one direction and therefore no commutator is required.

11. Classification according to the method of drive, as follows:

(a) **Belted-type motors and generators** are self-contained. This type of machine includes bearings, shaft extended for a pulley and a sliding base with belt-tightening device. An outboard bearing is usually provided with machines of larger capacity than 200 kw. at 600 rev. per min.

(b) **The engine-type generator** has its armature mounted on a continuation of the crank shaft of the engine, and **slow-speed units** are generally

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supplied without base, bearings, or shaft, these being furnished by the engine builder.

(c) **The direct-connected turbo-generator** has its armature shaft coupled directly to that of a steam turbine. In this type the construction of the generator is special on account of the high speed.

(d) **The geared turbo-generator** has its armature shaft connected to the shaft of a steam turbine through a reduction gear, so that a generator of moderate speed and simple construction may be used.

(e) **The water-wheel type generator** has its armature shaft coupled directly to that of a water wheel. Such a generator may be of either the horizontal or the vertical type and is generally supplied complete with base, bearings, shaft and coupling.

(f) **The back-geared type motor** embraces a speed-reduction gear as an element of the machine. The slow-speed shaft is supported in bearings attached to the frame.

12. **Classification according to special features of construction,** as follows:

(a) **Interpole machines** (Fig. 24) have small auxiliary poles which carry series windings and improve commutation.

(b) **Compensated machines** (Fig. 27) have series windings on the pole faces to neutralize armature reaction. Such machines may also have interpoles.

(c) **Miscellaneous.** Under this class may be included **mill motors,** used in rolling mills; **flame-proof motors** for mine service; **variable-speed generators,** for train lighting; etc. (Par. **183** to **215**).

ARMATURE WINDINGS

13. **The Gramme ring winding** is almost obsolete; examples of it are shown in Figs. 3, 5, and 6 merely to present clearly the meaning of the terms used in describing the various types of winding.

14. **A re-entrant winding** closes or re-enters on itself. **A singly re-entrant winding** closes on itself only after including all of the conductors; see Figs. 3 and 6. **A doubly re-entrant winding** closes on itself after including half of the conductors; see Fig. 5.

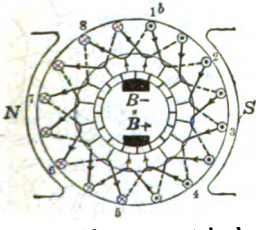


Fig. 5.—Doubly re-entrant duplex winding.

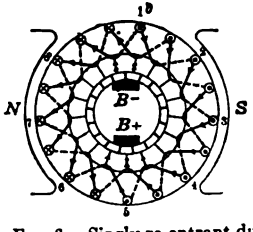


Fig. 6.—Singly re-entrant duplex winding.

15. **A simplex winding** has only two paths through the armature from each brush; see Fig. 3. **A duplex winding** has twice as many, or four paths, through the armature from each brush. In this winding each brush should cover at least two commutator segments; see Figs. 5 and 6. Although it is possible to use **multiplex** and **multiply re-entrant** windings, they are seldom found in modern machines. Even duplex windings are rarely used except for machines of very large current capacity.

16. **The drum winding** has coils shaped as shown in Fig. 7. At any instant, two sides of each coil are under adjacent poles. Since the number of conductors in each coil must be a multiple of two, the total number of conductors must be even. A winding made with coils of this shape must lie in two layers and is called a **double-layer winding.**

17. **Representation of drum windings.** Fig. 8 shows a double-layer

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drum winding corresponding to the Gramme ring winding in Fig. 3. It has the same number of conductors and the same number of paths through the armature, but only half the number of commutator segments. Conductors in the upper layer are represented by full lines and those in the bottom layer by dotted lines. The radial lines represent face conductors; the connecting lines on the inside represent the connections at the commutator end, and those on the outside represent the connections at the opposite end. For convenience the brushes are shown inside the commutator.

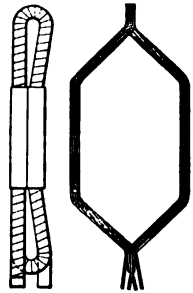


FIG. 7.—Coil group for double layer winding with two turns per coil and eight conductors per slot.

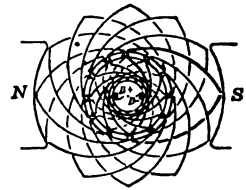


FIG. 8.—Simplex singly re-entrant drum winding.

18. Multiple winding. Fig. 9 shows a six-pole drum winding with six paths in parallel between the positive and the negative terminals. The three positive brushes are connected together outside of the machine by a copper ring T_+, and the three negative brushes are connected by a similar ring T_-. This winding is of the multiple type, that is, the number of armature circuits between terminals is a multiple of the number of poles.

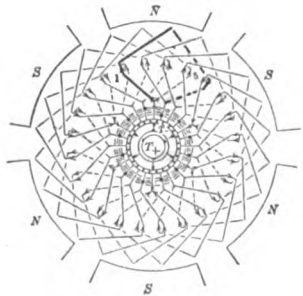


FIG. 9.

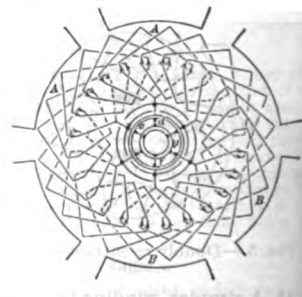


FIG. 10.

FIGS. 9 AND 10.—Simplex, singly re-entrant, full-pitch multiple winding with equalizers.

19. Equalizers. Fig. 10 shows a multiple-wound armature which is not central with the poles. The flux density in the air gaps A is greater than that in the air gaps B, and the voltage generated in a circuit under poles A is greater than that in a circuit under poles B, so that the generated voltage between c and d is greater than that between f and g; hence a **circulating current** will flow through the winding and brushes, causing sparking, additional loss and additional heating. This circulating current may be minimized by careful centering during erection, while the sparking may be pre-

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vented by providing a low-resistance path of copper between c and f, and also one between d and g (shown outside of the brush circle), so that the circulating current will flow through this path rather than through the brushes. These equalizer connections, as the low-resistance paths are called, do not eliminate the circulating current, but merely prevent it from passing through the brushes.

An armature is completely equalized by connecting together all commutator segments which should be at the same potential. However, it is usual to provide about 30 per cent. of the maximum number of equalizer connections and make their cross-section equal to half the cross-section of the armature conductor. The equalizer connections shown in Fig. 9 are located behind the commutator. In this position it is difficult to reach them for repair; consequently it is usual to connect the equalizers to the windings at the rear end of the machine.

20. The number of slots and the number of commutator segments, in a multiple-wound armature supplied with equalizers, should, for a simplex winding, be a multiple of $p/2$, the number of pairs of poles.

21. Pitch of winding. The winding shown in Fig. 9 is a **full-pitch winding** or one in which the width of the coil exactly equals the pole pitch. Fig. 11 shows part of a **short-pitch winding** or one in which the width of the coil is less than the pole pitch.

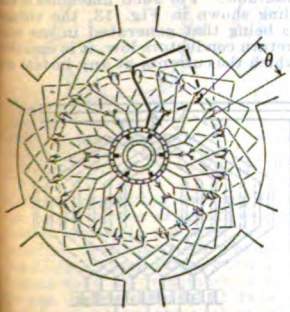


FIG. 11.—Simplex singly re-entrant short-pitch multiple winding.



FIG. 12.—Two-circuit progressive winding.

22. Two-circuit or series winding. Fig. 12 shows a six-pole drum winding with only two paths between the positive and the negative terminals. Only two sets of brushes are required and each brush short-circuits $p/2$ coils in series. Since the points a, b, and c are all at the same potential, and also the points d, e, and f, it is possible to place brushes on the commutator at each of these points, so that the current may be collected from three sets of brushes instead of from one, and a shorter commutator may be used. A machine with a two-circuit winding has generally as many brush sets as there are poles.

23. The number of commutator segments in a two-circuit winding must not be a multiple of the number of pairs of poles, for otherwise the winding, after it had passed once around the armature, would close upon itself. To be singly re-entrant, the winding must progress or retrogress by one commutator segment each time it passes around the armature, the condition for which is that the number of commutator segments must equal $(kp/2) \pm 1$, where k is a whole number and p is the number of poles.

24. Application of two-circuit winding. Each circuit of a two-circuit winding is made up of conductors passing under all the poles, so that no equalizers are required. Because of this, and also because only two sets

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of brushes are required, this type of winding is well suited for direct-current railway motors, inasmuch as the two sets of brushes for a four-pole motor are placed 90 deg. apart so that they may easily be inspected from the car.

25. Lap windings and wave windings. A multiple-wound armature is sometimes said to have **a lap winding** and an armature with a two-circuit winding is said to have a **wave winding.**

26. Dead coils. There are generally more coils than there are slots, and each coil may have more than one turn. A coil in this case is defined as the shortest winding element between two commutator segments. It is not always possible to put a proper two-circuit winding into a given armature. A 110-volt, four-pole machine, with forty-nine slots, forty-nine coils, and two conductors per slot, may have a two-circuit winding because it fulfills the condition that $49 = (24\ p/2) + 1$; when wound for 220 volts, however, four conductors per slot are required, and the number of coils is $98 = (49\ p/2) \pm 0$, which will not give a two-circuit winding. In such a case, one coil, called a dead coil, is not connected into the winding, its two ends being taped so as to completely insulate the coil. The machine, therefore, may have a two-circuit winding with ninety-seven active coils and ninety-seven commutator segments.

27. Turbo-generator windings. In turbo-generators the conductors are long and move at high speed, so that the voltage between adjacent commutator segments is often higher than desirable. For such machines it has been proposed to use the type of winding shown in Fig. 13, the voltage between adjacent commutator segments being that generated in one conductor. To keep the inductance of the return conductors low, it is desirable to group together return conductors in which the currents at any instant are in opposite directions.

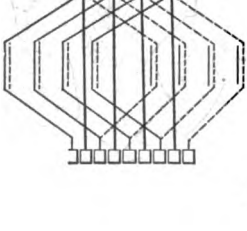


FIG. 13.—Winding with half-turn coil.

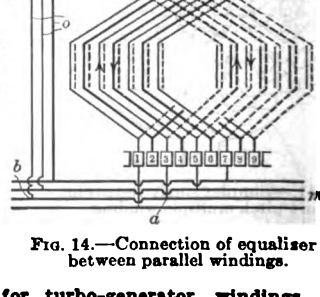


FIG. 14.—Connection of equalizer between parallel windings.

28. Equalizer connections for turbo-generator windings. The normal multiple-circuit doubly re-entrant duplex or multiplex windings can only be used to their full advantage when the voltage between the segments belonging to the different parallel windings is equally distributed, that is to say, the potential between segments 1 and 2 should be exactly half of the potential between segments 1 and 3; but without special means of bringing about this condition it is rather dangerous to use these windings. It may happen that the potential is very unevenly distributed between the segments, and this gives rise to very great equalizing losses over the brushes. The winding shown in Fig. 14 is a multiple-circuit doubly re-entrant duplex winding; the thin lines in the diagram indicate one of the parallel windings, the thick the other. The thin lines at the bottom of the diagram indicate the normal equalizer connections for the winding shown in thin lines, and the thick lines at the top indicate the normal equalizer connections for the winding shown in thick lines. The corresponding equalizer rings of the two parallel windings are connected through the equalizers indicated on the left of the diagram, and by means of these connections equa

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and the main exciting m.m.fs. exist together. Since the armature teeth are saturated at normal flux densities, the increase in flux density at f is less than the decrease at e, so that the total flux per pole is diminished by the cross-magnetising effect of the armature.

33. Demagnetising effect. Fig. 17 shows the magnetic field produced by the m.m.f. of the armature when the brushes are shifted through an angle

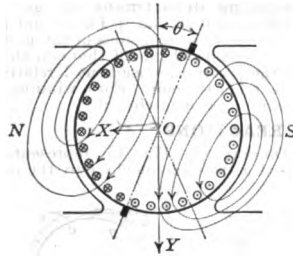


Fig. 17.

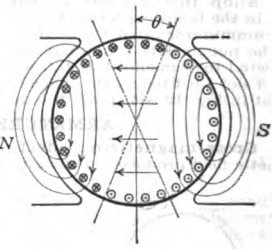


Fig. 18.

Figs. 17 and 18.—Demagnetising and cross magnetising effect.

θ so as to improve commutation (Par. 47). The armature field is no longer at right angles to the main field, but may be considered as the resultant of two components, one in the direction OY, called the cross-magnetising component, the effect of which is discussed in the last paragraph, and the other in the direction OX, which is called the demagnetising component because it is directly opposed to the main field. Fig. 18 shows the armature divided so as to produce these two components, and it may be seen that the demagnetising ampere-turns per pair of poles are

$$\left(\frac{ZI_a}{p}\right) \times \frac{2\theta}{180} \quad \text{(ampere-turns)} \qquad (2)$$

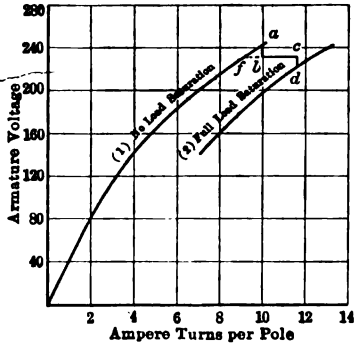


Fig. 19.

where $2\theta/180$ is generally about 0.2. Therefore the demagnetising ampere-turns per pole are

$$0.1\left(\frac{ZI_a}{p}\right) \text{(ampere-turns)} \quad (3)$$

34. No-load and full-load saturation curves. Curve 1, Fig. 19, shows the no-load saturation curve of a direct-current generator. When full load is put on the generator there is a decrease in flux and therefore a drop in voltage ab due to the armature cross-magnetising effect (Par. 32). A further voltage drop due to the armature demagnetising effect is counter-balanced by an increase in excitation of $bc = 0.1\ (ZI_a)/p$; also a portion cd of the generated e.m.f. is required in overcoming the internal resistance of the machine. With an excitation of 10,000 ampere-turns, the voltage at no load and normal speed equals 240 volts. At full load, with the same excitation, the terminal voltage equals 196 volts. In order that the full-load voltage may be the same as that at no load, the number of ampere-turns per pole which must be supplied by the series field is (13,400 − 10,000) = 3,400 ampere-turns.

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35. Relative strength of main exciting and armature magneto-motive forces. Inspection of Fig. 16 will show that, if the armature current have such a value that the cross ampere-turns at the pole tips, namely $\frac{1}{2}ZI_c/2p$, becomes equal to the exciting ampere-turns for tooth and gap, then the flux density will be zero under the pole tip toward which the brushes have been shifted (Par. 31). The quantity $ZI_c/2p$ is the number of armature ampere-turns per pole. The exciting ampere-turns per pole for tooth and gap are seldom less than 1.2 times the armature ampere-turns per pole for a machine which must operate without sparking up to 25 per cent. overload, and which has a series field to counteract the demagnetising effect of armature reaction. For a machine such as a shunt motor, which has no series field, the exciting ampere-turns for gap and tooth should not be less than 1.5 times the armature ampere-turns per pole.

COMMUTATION

36. Resistance commutation. Fig. 20 shows part of a machine with a full-pitch double-layer multiple winding, two conductors per slot, and with coils M undergoing commutation. The current in coils M is reversed as the armature moves and the brushes change from segments 1 and 5 to segments 2 and 6. If the brush contact resistance is large compared with the resistance and self induction of coil M then, in diagram B, the current $2I_c$

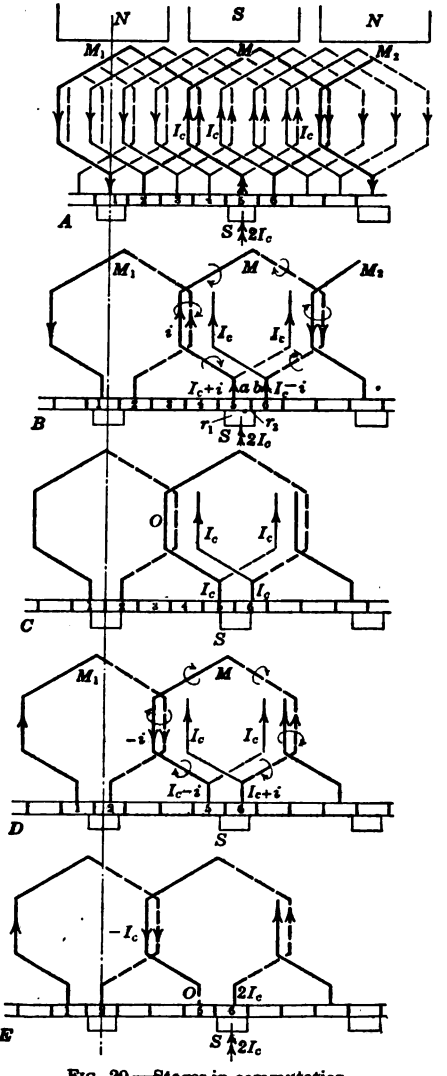


FIG. 20.—Stages in commutation.

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divides into two parts which are proportional to the areas of contact between the brush and segments 5 and 6 respectively, and the current density is uniform across the brush surface. In diagram *C* the two contact areas are equal; there is no tendency for current to pass round coil *M*, and the current density is again uniform across the brush surface. In diagram *D* the contact area between the brush and segment 5 is small while that between the brush and segment 6 is large; the larger part of the current therefore enters at segment 6 and the current in coil *M* is reversed, while the current $2I_c$ again divides into two parts which are proportional to the contact areas between the brush and the two commutator segments, and the current density is still uniform across the brush surface.

37. Perfect commutation is defined as such a change of current in the coil being commutated that the current density over the brush contact surface is constant and uniform.

38. The brush contact resistance depends on the brush material and, for carbon brushes, it decreases with increase of current density as shown in Fig. 21. The contact resistance with current flowing from commutator to brush is somewhat higher than with current flowing from brush to commutator.

39. Change of contact resistance with temperature. If the current density in a brush contact be suddenly increased, the contact resistance does not immediately decrease to the value given in Fig. 21, but gradually decreases as the temperature of the contact increases, and reaches a constant value after about 20 min. This explains why a machine will carry a considerable overload for a short time without sparking, whereas, if the overload be maintained, the machine will begin to spark as the brush temperature increases and the contact resistance decreases.

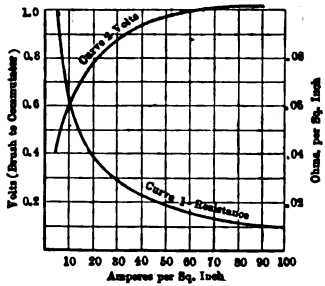


FIG. 21.—Brush contact resistance.

40. Current density in the brushes. For sparkless commutation, (1) the current density in the brush tip must not become infinite, and (2) the average amount of energy expended at the brush contact must be limited. For machines required to operate without sparking up to 25 per cent. overload, a rate of energy dissipation of 35 watts per sq. in. (5.5 watts per sq. cm.) may be allowed at full-load, so that the permissible current density depends upon the voltage drop across the brush contact. The better the commutation, the more nearly uniform is the current density in the brush contact, and the higher the average density which may be allowed.

41. Current density in the brush tip. The effect of coil resistance may generally be neglected, but that of self-induction must be considered. The e.m.f. of self-induction and mutual induction of coil *M* (Fig. 20) opposes the change of current in that coil, so that, in diagram *C*, at the end of half of the period of commutation, the current in the coils *M* has not become zero. When it does become zero, some time later, and the currents entering segments 5 and 6 are equal, the contact area with segment 5 is smaller than with segment 6 and the current density in the brush tip *S* is greater than normal. It may be shown theoretically that the tip density at the end of commutation becomes infinite* when $RT_c/(L+M)$ is less than unity,

where R is the resistance of the brush contact in ohms,
T_c is the time of commutation in seconds,
L is the coefficient of self-induction in henrys of one coil M,
and M is the coefficient of mutual induction in henrys between coil M and coils M_1 and M_2.

* Reid, on "Direct-current Commutation," *Trans.* A. I. E. E., Vol. XXIV.

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42. Copper leaf brushes can carry 150 amp. per sq. in. (23 amp. per sq. cm.) with a drop of 0.3 volt at the contact.

Carbon brushes can carry 35 watts per sq. in. (5.5 watts per sq. cm.), Par. **40**, for example 35 amp. per sq. in. (5.5 amp. per sq. cm.) with a drop of 1.0 volts at the contact.

43. Average reactance voltage. The criterion for sparkless commutation is, then (Par. **41**), that $RT_c/(L+M)$ shall be greater than unity, or that

$$2I_cR > \frac{2I_s}{T_c}(L+M) \qquad (4)$$

where $2I_s$ is the current entering the brush (Fig. 20). The latter quantity is called the average reactance voltage and the former is the voltage drop across one brush contact. It will be found that the higher the contact resistance and the lower the reactance voltage, the better is the commutation.

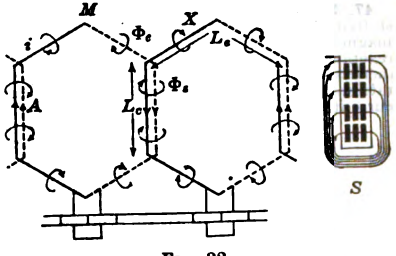


FIG. 22.

Fig. 22 shows the magnetic field encircling the short-circuited coils of a full-pitch multiple winding. The reluctance of the magnetic path may readily be calculated from which the value of the flux per unit current and $L+M$, the coefficient of self and mutual induction, are obtained. Deep slots decrease the reluctance of the magnetic path (for the same cross-section of conductor) and increase the reactance voltage, therefore they should be avoided if possible.

44. Effect of type of winding on reactance voltage. In the **short-pitch winding** shown in Fig. 11, the conductors undergoing commutation lie in different slots, and the reluctance of the magnetic path around the coils is greater, and the coefficient of mutual induction smaller, than in a **full-pitch winding.** The use of a short-pitch winding therefore lowers the reactance voltage and improves commutation, but, as shown in Fig. 11, it also reduces the effective interpolar space by the angle θ.

In the **two-circuit winding** with one set of positive and one set of negative brushes, shown in Fig. 12, each brush short-circuits $p/2$ coils in series, so that the reactance voltage is $p/2$ times that of a **multiple winding.** When, however, the number of brush sets is the same as the number of poles, there is a short commutation path around one coil and the commutation is improved.

45. Reactance voltage formula. Approximate results may be obtained by use of the following formula for the average reactance voltage.*

$$E_r = kS(\text{r.p.m.})I_c L_c T^2 \left(\frac{\text{poles}}{\text{paths}}\right)10^{-8} \quad \text{(volts)} \qquad (5)$$

where S is the number of commutator segments,
r.p.m. is the speed of the machine in rev. per min.,
I_c is the current in each armature conductor,
L_c is the frame length in inches (see Fig. 38),
T is the number of turns per coil between segments,

$\left(\frac{\text{poles}}{\text{paths}}\right)$ = 1 for multiple windings and $p/2$ for two-circuit windings,

$k = 1.6$ for two-circuit windings and for full-pitch multiple windings,

and

$k = 0.93$ for short-pitch multiple windings.

Deep slots increase the reactance voltage above this value.

* Gray. "Electrical Machine Design," p. 84.

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46. Effect of brush arc. An increase in the brush arc has no effect on the reactance voltage because, while it increases the number of coils in series at short circuit, it decreases the time of commutation in the same ratio, and the reactance voltage remains unchanged. On the other hand, a wide arc may cause sparking by starting commutation in the coils before they are in a reversing field, or by keeping them short-circuited until they are in too strong a field. To minimise this trouble make the proportions such that,

$$\text{brush arc} < \left(\frac{\text{pole pitch}}{12}\right) \times \left(\frac{\text{commutator diameter}}{\text{armature diameter}}\right) \qquad (6)$$

where all dimensions are in inches. Furthermore, the brush should not cover more than three commutator segments except in machines of low reactance voltage, otherwise there will be large circulating currents in the brush face.

47. Shifting of brushes. To improve commutation, the brushes are shifted from the neutral position, so that the short-circuited coils are in a magnetic field and an e.m.f. (E_s) is generated in them which opposes the reactance voltage and improves commutation. As the current in the machine increases, the reactance voltage increases with it. To have perfect commutation at all loads, the voltage E_s must maintain an unvarying ratio to the current. This is only possible when the distance by which the brushes are moved from the neutral position increases as the current increases. Modern machines must operate from no load to 25 per cent. overload without sparking and without shifting of the brushes during operation. In these machines the brushes are permanently shifted (at the time of erection) from the neutral position until the voltage E_s is so large that sparking takes place at no load.

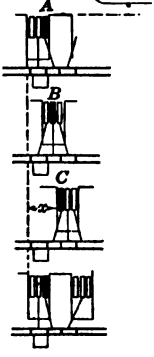


FIG. 23.—Commutation with several coils per slot.

48. Number of slots per pole. Fig. 23 shows three of the stages in the commutation of a machine with six coil sides per slot. The commutator segments are evenly spaced while the coils, being in slots, are not. Between the instant when the brush breaks contact with coil *A*, and the instant it breaks with coil *C*, the slot has moved through a distance x, so that if the magnetic field in which the coils are commutated is suitable for coil *A*, it is too strong for coil *C*, and the latter will therefore be badly commutated, every third commutator segment being blackened. The distance x is equal to the slot pitch minus the width of one commutator segment. To minimise this trouble, a machine should have more than twelve slots per pole. Large machines have generally more than fourteen slots per pole.

49. Limits of reactance voltage. Experience shows that when the following conditions are fulfilled, namely:

(1) Number of slots per pole is greater than twelve,

(2) Brush arc is less than one-twelfth of the pole pitch measured at the commutator surface,

(3) Pole arc is less than seven-tenths of the pole pitch, and

(4) Ampere-turns for air-gap and teeth are greater than 1.2 to 1.5 times the armature ampere-turns per pole (Par. **35**): then the reactance voltage calculated by Eq. 5 (Par. **45**) should be

(1) Less than seven-tenths of the voltage drop per pair of brushes, with brushes in neutral position, and

(2) Less than the full voltage drop per pair of brushes, with the brushes shifted to improve commutation.

A machine with a two-circuit winding will commutate about 20 per cent. better than would be indicated by the value of reactance voltage obtained from Eq. 5 (Par. **45**), while the commutation of a machine with a short-pitch winding will be about 30 per cent. worse than indicated, because of the reduction of the effective interpolar space (Par. **44**).

50. Shunt, compound and series machines. Due to armature reaction, the flux at the pole tip toward which the brushes are shifted decreases with

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increase of armature current (Par. 31). This decrease is kept within reasonable limits by the use of a strong exciting field (Par. 35) and is less in a compound machine than in a shunt machine operating on constant excitation. In the series machine the main exciting m.m.f. and the armature m.m.f. increase together, and the flux at the commutating pole tip may increase or decrease, depending on the relative strength of field and armature.

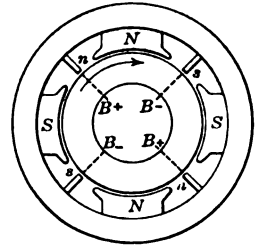


FIG. 24.—Magnetic circuit of interpole generator.

51. Interpoles. An interpole generator is shown diagrammatically in Fig. 24, where n and s are auxiliary poles which have a series winding so connected that their strength increases with the armature current. To improve commutation in a non-interpole generator, the brushes are shifted forward in the direction of motion, so that B_+ would come under the tip of the N pole and B_- under the tip of the S pole. In the interpole machine the auxiliary pole n is placed opposite the brush B_+ and the auxiliary pole s opposite the brush B_-.

52. Interpole excitation. The interpole must have a m.m.f. equal and opposite to that of the cross-magnetizing effect of the armature, namely, $ZI_c/2p$ ampere-turns per pole (Par. 30) and, in addition, a m.m.f. which can send across the gap a flux large enough to generate in the short-circuited coil an e.m.f. equal and opposite to the reactance voltage. In order that the interpole flux may be always proportional to the current, the interpole magnetic circuit must not be allowed to become saturated.

53. The effective interpole arc is represented by the expression $W_{ip}+2\delta$ (see Fig. 25) and should be of such proportions that while the current in a conductor is being commutated, the slot carrying that conductor is in the interpole field.



FIG. 25.—Interpole width.

54. The reluctance of the interpole air-gap should vary as little as possible for different positions of the armature, otherwise the interpole field will be pulsating. The effective interpole arc should therefore be a multiple of the slot pitch; it is generally made about 15 per cent. of the pole pitch and, to minimize the interpole leakage flux, the main pole arc is not more than about 65 per cent. of the pole pitch.

55. The axial length of the interpole in inches is given by the formula,*

$$L = \frac{24 \times \text{core length in inches} \times \text{amp. cond. per in.}}{\text{interpole gap density in lines per sq. in.}} \qquad (7)$$

The ampere-conductors per in. (Par. 59) seldom exceed 900, and, with an interpole gap density of 45,000 lines per sq. in. (7,000 lines per sq. cm.), the interpole circuit will not be saturated up to 50 per cent. overload; the interpole length, therefore, need not exceed half the frame length, if there are as many interpoles as there are main poles and if the overloads do not exceed 50 per cent.

56. The interpole ampere-turns per pole for a newly designed machine are usually made equal to 1.4 times the armature ampere-turns per pole (Par. 52). This is generally too large, so adjustment must be made after the machine is erected.

57. Flashing over† is generally caused by a sudden change of load. Fig. 26 shows a representation of the armature cross-field in a loaded machine. A sudden change of load alters the value of the cross-flux, and a voltage

*Gray. "Electrical Machine Design," p. 94.

†Lamme, "Physical Limitations in Commutating Machinery," *Trans.* A. I. E. E., Vol. 34, pp. 1559–1614, Aug., 1915, and Linebaugh and Burnham, "Protection from Flashing for D. C. Apparatus," *Proc.* A. I. E. E., Vol. 37, pp. 617–628, June, 1918.

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proportional to the rate of change of flux is generated in coil *a*. This may increase the voltage that already exists between adjacent segments to such a value that arcing starts, and then the machine flashes over from brush to brush, particularly if the commutator is dirty. Machines with badly distorted fields and a high average voltage between commutator segments are especially likely to flash over.

58. Compensating windings. For such service as the operation of reversing rolling mills, the current in the motors may change suddenly from full-load value in one direction to three times full-load value in the opposite direction. For such machines the average voltage between adjacent commutator segments, which is equal to the terminal voltage divided by the number of commutator segments per pole, should not exceed

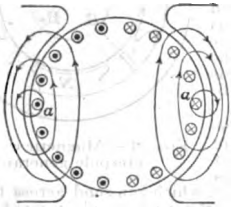


FIG. 26.

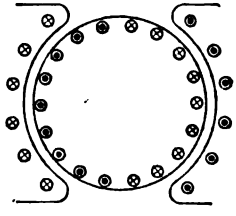


FIG. 27.

FIGS. 26 AND 27.—Armature field with and without compensating windings.

about 15, otherwise compensating windings will be required to prevent flashing over. The compensating winding is carried by the pole face, and is in series with and has the same number of ampere-turns per pole as the armature. However, the current passes in the opposite direction to that in the armature and thus, as shown in Fig. 27, the armature field is completely neutralized. For further discussion of the subject of commutation see the references below.*

ARMATURE DESIGN

59. Output equation. The output of a machine is proportional to the armature volume, and the output equation is

$$D_a^2 L_c = \frac{\text{watts} \times 60.8 \times 10^7}{\text{r.p.m.} \times \mathfrak{B}_g \times q \times \Psi} \quad \text{(cu. in.)} \qquad (8)$$

where D_a is the armature diameter in inches,
L_c is the frame length in inches (Fig. 38),
$\mathfrak{B}_g$ is the apparent gap density in lines per sq. in.,
Ψ is the per cent. enclosure (= pole arc pole ÷ pitch), and
q is the ampere-conductors per in. ($= ZI_c/\pi D_a$).

60. The e.m.f. equation for all types of direct-current generators is:

$$E = Z\phi_a \left(\frac{\text{r.p.m.}}{60}\right)\left(\frac{\text{poles}}{\text{paths}}\right)10^{-8} \quad \text{(volts)} \qquad (9)$$

where E is the generated voltage between terminals,
Z is the total number of face conductors,
ϕ_a is the flux per pole which crosses the air-gap and is cut by the armature conductors,
r.p.m. is the armature speed in revolutions per min.
"paths" refer to the number of parallel circuits (electric) through the armature.

* Arnold, "Die Gleichstrommaschine," Vol. I and II; Hawkins and Wallis, "The Dynamo," Vol. II; Baily and Cleghorne, *Journal* of Inst. of Elec. Eng.; Vol. XXXVIII; Gray, "Electrical Machine Design;" Hobart, "Dynamo Design," Lamme, *Trans.* A. I. E. E., Vol. XXX, p. 2359.

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61. Another output equation, readily obtained from the e.m.f. equation, is given by

$$\frac{\text{watts}}{\text{r.p.m.}} = \left(\frac{ZI_a}{\text{paths}}\right)(\phi_a \times \text{poles})\,\frac{1}{60 \times 10^8} \qquad (10)$$

where (ZI_a/paths), called the **electric loading,** is the total number of ampere-conductors on the armature periphery. The larger the electric loading, the more copper and the less iron there is in the machine. The **magnetic loading,** as the quantity $(\phi_a \times \text{poles})$ is termed, is the total flux entering the armature. The larger the magnetic loading, the more iron and the less copper there is in the machine.

62. The gap density ($\mathfrak{B}_g$) is limited by the density at the bottom of the teeth; the greater the diameter, the less the tooth taper, and the higher the gap density for a given tooth density at the root. The relation between $\mathfrak{B}_g$ and D_a is given in Fig. 28.

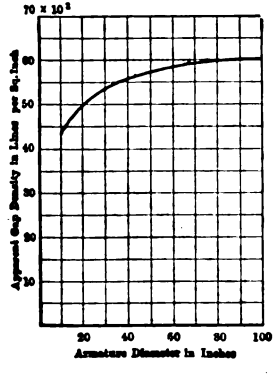


FIG. 28.

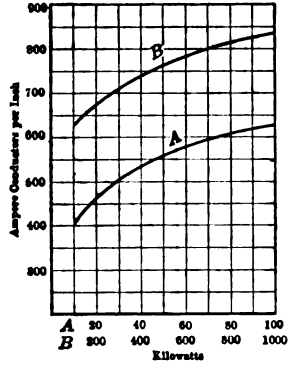


FIG. 29.

63. The ampere-conductors per in. (q) are limited by heating and by commutation. If q is large, the copper section must be large and the slots deep in order to keep down the temperature, but deep slots tend to cause sparking. It is found that q depends principally on the output of the machine, as shown in Fig. 29.

If the speed for a given output be increased, a smaller diameter can be used, and the peripheral velocity will not be greatly increased. Since the small machine is not so well ventilated as the large machine, see Fig. 31, the same value of q should be used in each case.

64. Relative cost factor. A certain ratio k, which is equal to the magnetic loading divided by the electric loading, will give the cheapest machine. Then

$$\frac{\text{watts}}{\text{r.p.m.}} = \text{a const. (electric loading) (magnetic loading.) Par. 61.}$$

$$= \text{a const. (electric loading)}^2 \qquad (11)$$

and the relation between the watts per rev. per min. and the electric loading, given in Fig. 30, may be used in preliminary design. The value of k is affected by the cost of labor and material and by the conditions of manufacture.

65. Number of poles. A pole of circular cross-section has the largest section for the shortest mean turn. If the pole be rectangular, then that with a square section has the largest area for the shortest mean turn. For economy in copper, the ratio of pole pitch to frame length will generally have a value between 1.1 and 1.7.

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66. The armature ampere-turns per pole seldom exceed 7,500 in non-interpole machines. A larger number requires a long pole pitch, long end connections, a large number of exciting ampere-turns per pole, long poles, and a yoke of large diameter. For interpole machines, the main field need not be so strong relatively to the armature field as in non-interpole machines, and a reasonable limit for the armature ampere-turns per pole is 10,000.

67. A simple procedure for armature design is given in the following:

ZI_c, the number of ampere-conductors, is obtained from Fig. 30.

$q = ZI_c/\pi D_a$, the number of ampere-conductors per in., is obtained from Fig. 29.

D_a, the armature diameter, is next determined.

$\mathfrak{G}_g$ is obtained from Fig. 28.

L_c is found by substitution in Eq. 8, Par. **59.**

p, the number of poles, is so chosen that the pole pitch divided by L_c equals 1.1 to 1.7.

ϕ, the flux per pole = 0.7 (pole pitch) $\times L_c \times \mathfrak{G}_g$, assuming the pole enclosure = 0.7.

Z, the number of armature conductors, is found from Eq. 9, Par. **60.**

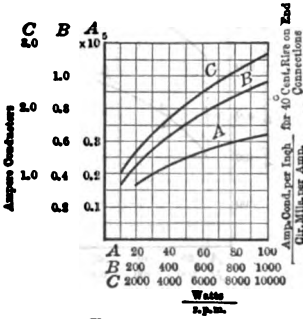


FIG. 30.

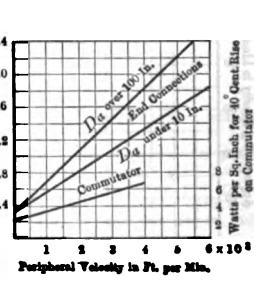


FIG. 31.

The winding is then so chosen that the reactance voltage will be below the desired limit. A two-circuit winding is the cheapest, and a winding with two turns per coil is cheaper than one with only one turn per coil.

68. The commutator diameter (D_c) is made equal to six-tenths of the armature diameter so as to have reasonably long "necks" (coil leads), but a peripheral velocity greater than 3,500 ft. per min. (1,070 m. per min.), is undesirable. One objectionable feature of the turbo-machine is that its commutator speed may run as high as 7,000 ft. per min. (2,140 m. per min.).

69. Brush design. The brush arc should not exceed the value $\left(\frac{\text{pole pitch}}{12}\right)\left(\frac{\text{comm. dia.}}{\text{arm. dia.}}\right)$. The volts drop per pair of brushes should be chosen to suit the reactance voltage (Par. **49**). The energy at the brush contacts is limited to 35 watts per sq. in. (5.5 per sq. cm.) (Par. **40**).

70. Example of armature design. It is required to determine approximate dimensions for a direct-current generator of the following rating: 400 kw., 240 volts, 1,670 amp., 200 rev. per min. The results, determined in consecutive order, are as follows:

ZI_c, ampere-conductors,	$= 1.33 \times 10^5$
q, ampere-conductors per in.,	$= 733$
D_a, armature diameter,	$= 58$ in.
B_g, apparent gap density,	$= 58{,}000$ lines per sq. in.
L_c, frame length,	$= 12$ in.

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p, poles,		= 10	
τ, pole pitch,		= 18.2 in.	
ϕ, flux per pole,		$= 8.8 \times 10^6$	
Z, total face conductors,	= 164	= 820	= 820
Winding,	1-turn ser.	2-turn mult. short pitch	1-turn mult. short pitch
S, commutator segments,	= 82	= 205	= 410
EV, reactance voltage,	= 13	= 3.1	= 1.5
D_c, commutator diameter,			= 35 in.
Brush arc,			= 0.91 in.
Volts per pair of brushes,			= 2
Amp. per sq. in. brush contact,			= 35
Brush length,			= 10.5 in.
F, commutator face,			= 13 in.

If the winding were series, or two-turn multiple, the reactance voltage would be too high and interpoles would be required.

Comparative designs should be worked out with both larger and smaller armature diameters and with different numbers of poles; then a choice should be made, and the design completed as below.

The final or **detailed design** is worked out in the following order. The probable number of total face conductors is 820, from the preliminary design. The number of slots per pole should be greater than fourteen and the total number of slots greater than 140; the nearest number of slots that will give an even number of conductors per slot is 200. Therefore

Slots	= 200
Conductors per slot	= 4
Coils	= 400
Commutator segments	= 400
Winding	1-turn multiple

Ampere-conductors per in. $= 167 \times 800/\pi \times 58 = 730$

$$\frac{\text{Ampere-conductors per in.}}{\text{Cir. mils per amp.}} = 1.3 \text{ for 40 deg. cent. rise, from Fig. 31.}$$

Cir. mils per amp.	= 560
Amp. per conductor at full load	= 167
Section of conductor	= 93,000 cir. mils = 0.073 sq. in.

Slot opening = 0.47 × (slot pitch) in large machines
= 0.52 × (slot pitch) in small machines

For a first approximation, therefore

Slot pitch = 0.91 in.
Slot opening = 0.43 in.

0.064 width of slot insulation (Fig. 47)
0.04 clearance between coil and core
0.326 available space for copper and conductor insulation.

Use flat strip, as in Fig. 47, with two conductors in the width of the slot; make the strip 0.14 in. wide and insulate it with half-lapped cotton tape.

Depth of conductor = 0.073/0.14 = 0.52 in.; increase this to 0.55 in. to allow for rounding of the corners.

Slot depth is found as follows:

0.55 = depth of each conductor
0.024 = insulation of each conductor
0.084 = depth of slot insulation (Fig. 47)
0.658 = depth of each insulated coil
2 = number of coils in depth of slot
1.316 = depth of coil space
0.2 = thickness of stick at top of slot
1.516 = necessary slot depth; make it 1.6 in.

The tooth flux density should now be checked to make sure that it is not too high, see Par. **123**, and the internal diameter of the armature made such that the flux density in the armature core shall not exceed 85,000 lines per sq. in.

71. Effect of interpoles. When interpoles are used, the reactance voltage is no longer a limiting factor in the design, so that deep slots may be used and a large amount of copper put on each inch of the periphery. For interpole machines, the value of q, the ampere-conductors per in., will

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generally be 20 per cent. greater than given in Fig. 29. The commutating fringe under the pole tip is not used, so that the ratio of the exciting ampere-turns per pole for gap and teeth to the armature ampere-turns per pole, which is seldom less than 1.2 for non-interpole machines, is generally made about 0.8 for similar machines with interpoles. There is therefore a large saving in field copper, and in pole and yoke material.

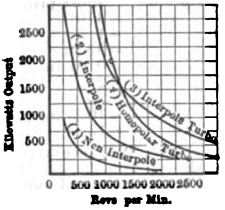


FIG. 32.—Maximum output curves.

72. Speed limitations in design.* If the peripheral velocity of a machine is fixed, the output can be increased only by increasing the frame length, the number of conductors, or the current per conductor, all of which increase the reactance voltage; so that, after a certain output has been reached, interpoles must be supplied or the peripheral velocity increased.† Fig. 32 shows the maximum output that can be obtained for a given speed, the peripheral velocity being taken as 6,000 ft. per min. (1,830 m. per min.) for machines of ordinary construction, and 15,000 ft. per min. (4,600 m. per min.) for turbo-machines. The high-speed turbo-machine is not too satisfactory as regards efficiency, commutation, and heating and the tendency is to gear a high-speed turbine to a moderate speed generator through a reduction gear.

FIELD DESIGN

73. The magnetic circuit is well shown in general in Fig. 38, where the closed dot-and-dash line indicates the complete path through one pair of poles, two air-gaps, the armature and the yoke, all in series. There are as many paths similar to this one, in a multipolar machine, as there are poles. This path, of course, is the path of the useful flux, and does not take into consideration the leakage flux.

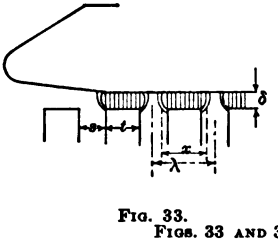


FIG. 33.

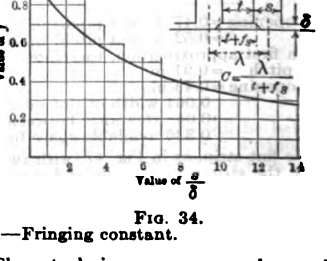


FIG. 34.

FIGS. 33 AND 34.—Fringing constant.

74. The fringing constant.‡ The actual air-gap area per pole equals $(\psi_T L_e)x/\lambda$, Par. 75, where λ/x (Fig. 33) is the fringing constant C. Now $x = t + fs$ where f depends on the slot width s and on the air-gap clearance δ and may be obtained from Fig. 34. Then

$$C = \lambda/x = (t+s)/(t+fs) \qquad (12)$$

For the machine shown in Fig. 35:

$s/\delta = 0.43/0.3 = 1.44$
$f = 0.78$ from Fig. 34.
$C = (0.48+0.43)/(0.48+0.78\times 0.43) = 1.12$

* Hobart and Ellis. "High Speed Dynamo-electric Machinery."
† Gray. "Electric Machine Design," p. 142.
‡ Carter, *Electrical World and Engineer*, Nov. 30, 1901; Hele-Shaw, Hay and Powell; *Jour.* of Inst. of Elec. Eng., Vol. XXXIV, p. 21.

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There is a small amount of fringing at the pole tips which tends to increase the air-gap area, but this effect is counterbalanced by the effect of the increase in the air-gap clearance near the pole tips. The fringing constant for the vent ducts may be found in the same way as for the slots, but is so nearly equal to unity that the calculation is seldom made.

75. The magnetic areas: In Fig. 38, let

A_y = the yoke area;

A_p = the pole area = $W_p L_p$ for solid rectangular poles and = 0.95 $W_p L_p$ for poles built of laminations;

A_t = the tooth area per pole = $(\psi N/p) t L_n$ where L_n, the net length of the core equals 0.9 (L_c − the space taken by the ducts), ψ is the ratio pole arc/pole pitch, and N is the total number of teeth.

A_c = the armature core area = $d_c L_n$;

A_g = the apparent gap area per pole = $\psi_\tau L_a$;

A_{ag} = the actual gap area per pole = A_g/C, where C is a constant greater than unity, which takes into account the effect of the slots in reducing the gap area.

These areas are determined, in the first instance, by dividing the total flux in a given portion of the magnetic circuit, by the allowable flux density.

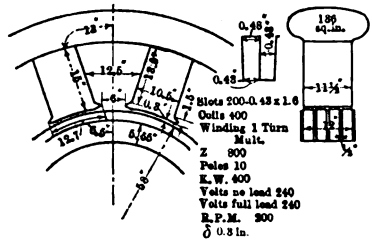


FIG. 35.—Fringing constant study.

76. Flux density in the air-gap. The apparent gap density which may be allowed for an armature of specified diameter is shown by the curve in Fig. 28. It will be noted that $\mathfrak{B}_g = \phi_a/A_g$, where A_g is the apparent gap area per pole. The apparent gap area is connected with the actual gap area by the relation $A_g = CA_{ag}$, where C (fringing constant) is greater than unity. Conversely, the apparent gap density is connected with the actual gap density by the same constant, and $B_{ag} = CB_g$.

77. Flux densities in the iron are given below. These are average values found in standard machines designed for continuous duty.

	Expression for	Material of magnetic circuit	Lines per sq. in.	Lines per sq. cm.
$\mathfrak{B}_y$, the yoke density	$\frac{\phi_a}{2A_y}$	cast iron....	40,000	6,200
		cast steel....	80,000	12,400
$\mathfrak{B}_p$, the pole density	$\frac{\phi_a}{A_p}$	laminations..	95,000	14,700
		cast steel....	90,000	14,000
$\mathfrak{B}_t$, the apparent tooth density (maximum).....	$\frac{\phi_a}{A_t}$	laminations.	150,000	23,000
$\mathfrak{B}_c$, the core density	$\frac{\phi_a}{2A_c}$	laminations.	85,000	13,000

78. The apparent tooth density ($\mathfrak{B}_t$) is greater than the actual density in the teeth because, since the teeth are highly saturated at normal densities, a considerable amount of flux passes down the slots, vent ducts, and air spaces between the laminations. The relation between the apparent and the actual tooth density is given in Fig. 36, for the magnetization curves shown in Fig. 37 and for the ratio $L_n/L_c = 0.8$.

79. Leakage factor. Fig. 38 shows two poles of a multipolar machine;

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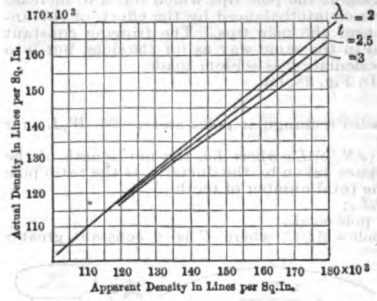


FIG. 36.—Armature tooth densities.

ϕ_m, the total flux per pole, consists of the flux ϕ_a which crosses the air-gap and is cut by the armature conductors, and the leakage flux ϕ_ℓ which crosses between the poles but does not enter the armature. The ratio ϕ_m/ϕ_a, called the leakage factor, is greater than unity; its value may be calculated with a fair degree of accuracy if the dimensions of the magnetic circuit are known, but for direct-current machines it is usual to assume a value of leakage factor and, for a first approximation, the following table may be used for the type of machine shown in Fig. 38.

	Leakage factor
Four-pole machines up to 10 in. armature diameter....	1.25
Multipolar machines between 10 in. and 30 in. diameter..	1.2
Multipolar machines between 30 in. and 60 in. diameter..	1.18
Multipolar machines greater than 60 in. diameter.....	1.15

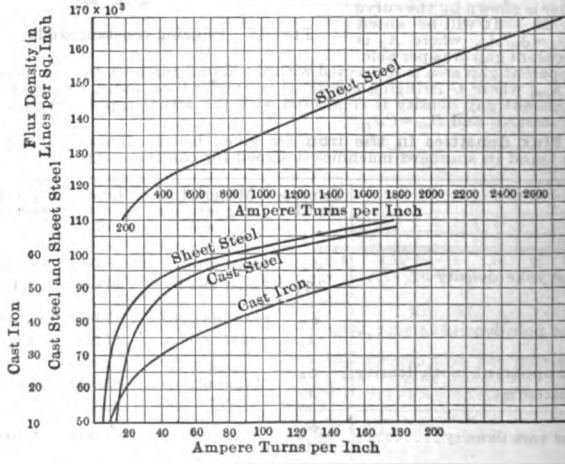


FIG. 37.—Magnetization curves.

80. Calculation of the leakage factor.* Fig. 39 shows part of a machine with a large number of poles. The total leakage flux per pole is

$$\phi_\ell = \phi_1 + \phi_2 + \phi_3 + \phi_4 \qquad (13)$$

*The derivation of these formulæ is given in Gray, "Electrical Machine Design," page 51, for other cases see Hawkins and Wallis, "The Dynamo," Vol. I, p. 471.

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where

$$\phi_1 = 13k(nI)_{g+t}\,\frac{L_s h_s}{l_1} \tag{14}$$

$$\phi_2 = 19k(nI)_{g+t}\,h_s \log_{10}\left(1+\frac{\pi W_s}{2l_1}\right) \tag{15}$$

$$\phi_3 = 6.5k(nI)_{g+t}\,\frac{L_p h_p}{l_3} \tag{16}$$

$$\phi_4 = 9.5k(nI)_{g+t}\,h_p \log_{10}\left(1+\frac{\pi W_p}{2l_3}\right) \tag{17}$$

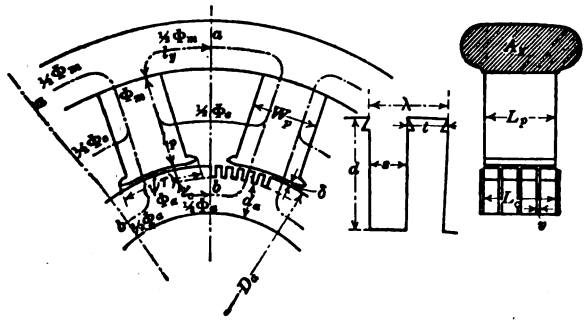


FIG. 38.—The paths of the main and the leakage fluxes.

and k is equal to unity for inch units and to $1/2.54 = 0.3937$ for centimeter units. For a given value of ϕ_g, the flux crossing the air-gap, the value of $(nI)_{g+t}$, the necessary ampere-turns per pole for gap and teeth, may be found; and, substituting this value in the above formulas, the corresponding value of ϕ_s may be found. The leakage factor $= 1 + \phi_s/\phi_g$.

81. Calculation of field ampere-turns per pole. The total ampere-turns per pole required to establish the necessary flux in the magnetic circuit may be analyzed into a series of components. The natural subdivision follows the several different members or elements which go to make up the complete circuit. These would include the yokes, the field cores, the air-gaps, the armature teeth and the armature core. Since the field poles are structurally duplicates of each other, except where interpoles are used, it is natural to confine the calculations of required ampere-turns to a single field pole. Fig. 40 shows the unit magnetic circuit for a multipolar machine, or that part of the total magnetic structure which corresponds to one field pole and simply needs repeated application to build up the whole structure. This unit magnetic circuit comprises one complete field core, one complete air-gap, one complete group of armature teeth under a single pole

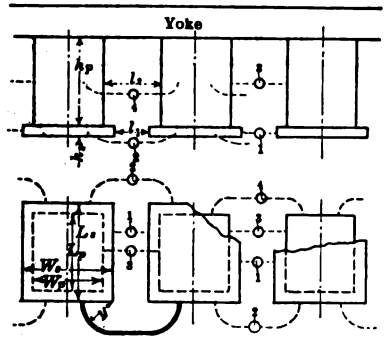


FIG. 39.—The leakage paths.

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face, two half-yokes in parallel and two half-armature cores in parallel. The total number of ampere-turns, at no load, may be expressed as

$$nI = (nI)_g + (nI)_a + (nI)_y + (nI)_t + (nI)_g \qquad (18)$$

where the several quantities in the formula are as follows:

$(nI)_y$ represents the number of ampere-turns required to establish the flux $\phi_m/2$ through a length of yoke equal to l_y in Fig. 38; this length is one-half the total length of the yoke circuit from pole to pole. In a single-yoke machine, such as the horse-shoe bipolar type, with two field coils, the full value of flux, or ϕ_m, should be assumed instead of $\phi_m/2$.

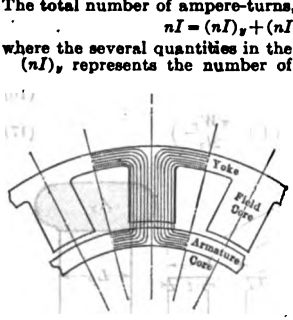


FIG. 40.—Unit magnetic circuit of multipolar machine.

$(nI)_a$ represents the number of ampere-turns required to establish the flux $\phi_a/2$ through a length of armature core equal to l_a in Fig. 38.

$(nI)_p$ represents the number of ampere-turns required to establish the flux ϕ_m through the field core, which has a length of l_p as shown in Fig. 38.

$(nI)_t$ represents the number of ampere-turns required to establish the flux ϕ_a through one set of armature teeth under one pole face.

$(nI)_g$ represents the number of ampere-turns required to establish the flux ϕ_a through one air-gap.

The calculation of ampere-turns in each case, except for the air-gap, is carried out by taking different values of flux density $\mathfrak{B}$ and obtaining the proper value of ampere-turns per in. from the curves in Fig. 37; the latter is then multiplied in each instance by the length of the corresponding portion of the magnetic circuit, in inches.

The required number of ampere-turns for the air-gap, in terms of inch units, is given by

$$(nI)_g = \frac{C\,\mathfrak{B}_g\,\delta}{3.20} \qquad (19)$$

and in terms of centimeter units, by

$$(nI)_g = \frac{C\,\mathfrak{B}_g\,\delta}{1.26} \qquad (20)$$

The quantity C is the fringing constant (Par. 75).

82. Excitation for tapered teeth. When the armature teeth are tapered, the flux density is not uniform throughout the total depth of the tooth. The tooth length must therefore be divided into a number of short lengths, the flux density and the corresponding ampere-turns per in. length found in each case, and the average value multiplied by the tooth length to give $(nI)_t$. This process can be shortened by use of the series of curves shown in Fig. 41; if k, the ratio between the actual flux densities at the bottom and at the top of the tooth, is known, the average ampere-turns per in. can be found directly.

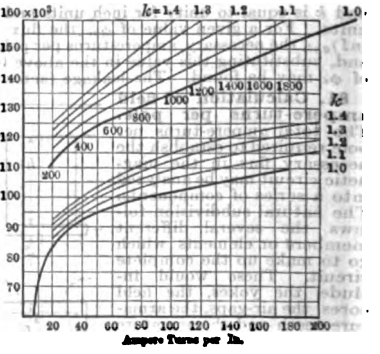


FIG. 41.—Magnetisation curves for tapered teeth.

83. Calculation of the no-load saturation curve. Taking the example of the ten-pole machine shown in Fig. 35, the following calculations must be carried out in order to obtain a series of points from which to plot the no-load saturation curve.

L_a = the net axial length of armature core = $0.9\,(12 - 3\times 0.5) = 9.45$ in.
A_y = the yoke area = 136 sq. in.

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87. The minimum length of field coil to give the necessary radiating surface for cooling is given by the formula*

$$L_f = \frac{n_f I_f}{1{,}000} \sqrt{\frac{\text{length of mean turn}}{\text{external periphery} \times \text{watts per sq. in.} \times d_f \times sf \times 1.27}} \qquad (22)$$

where L_f is the length of the field coil in inches, Fig. 42,
d_f is the depth of the field coil in inches,
sf is the space factor of the winding and may be found from Fig. 43.
The allowable watts per sq. in. of surface B, Fig. 42, may be found from Fig. 44.



FIG. 42.—Field coil length.

88. The weight of field coil for a given machine is equal to $\sqrt{d_f}$ multiplied by a constant. The larger the value of d_f, the shorter the length L_f, the smaller the radiating surface and the lower the permissible loss in the coil. Since the section of the field coil wire is fixed (because it depends only on the ampere-turns and the voltage per coil, Par. **86**), a lower permissible loss can be obtained only by the use of a smaller current I_f, a larger number of turns n_f, and therefore a more expensive coil. It must not be overlooked, however, that when d_f becomes smaller and the field coil becomes cheaper, the value of L_f increases and therefore the cost of the poles and the yoke increases. The most economical value for d_f must be determined by trial; an average value is 2 in.

89. Example of field system design. The armature of a ten-pole, 240-volt no-load, 240-volt full-load, 1,670 amp., 200 r.p.m. generator is shown drawn to scale in Fig. 35; it is required to design the field system, which is not supposed to be given.

The following data are taken from Par. **83.**

$\phi_m = 10.5 \times 10^6$
$\phi_a = 9 \times 10^6$
$nI_t = 2{,}080$
$\mathfrak{B}_g = 59{,}000$ lines per sq. in.

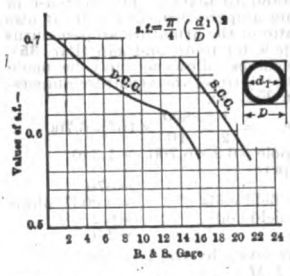


FIG. 43.—Space factor for wire.

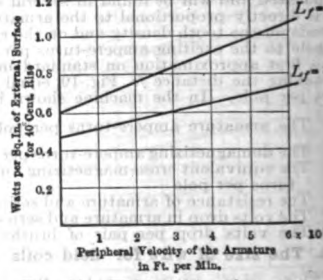


FIG. 44.—Field-coil heating constant.

(a) Calculation of the air-gap clearance.

$(nI)_g + (nI)_t = 1.2$ times the armature ampere-turns per pole, from Par. **35**,
$= 1.2\ (800 \times 167/2 \times 10) = 8{,}100$
$(nI)_t = 2{,}080$ see above
$(nI)_g = 6{,}020$,
$C\delta = 3.2 \times 6{,}020/59{,}000$, from Par. **81**,
$= 0.328$ in.,
$C = 1.12$ from Fig. 34,
$\delta = 0.29$ in. (make it 0.3 in.).

* Gray. "Electrical Machine Design," p. 66.

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(b) **Calculation of approximate dimensions for the magnetic circuit.**

Assume the no-load excitation = $1.25[(nI)_g+(nI)_t]$
= 10,100 ampere-turns per pole.

Next find L_f for the shunt coil from eq. 22 (Par. 87), where d_f is assumed to be 2 in.; sf is assumed to be 0.6, from Fig. 43; the allowable watts per sq. in. = 0.6 from Fig. 44; the external periphery of the field coil equals 1.2 times the length of the mean turn, approximately; therefore L_f = 10 in., approximately; the latter should be increased 30 per cent. to allow for the series coil.

The pole area = ϕ_m/G_p = $10.5\times10^6/95{,}000$ = 112 sq. in.

The yoke area = $\phi_m/2G_y$ = $10.5\times10^6/2\times40{,}000$ = 132 sq. in.

(c) **Saturation curves.** From these dimensions the magnetic circuit is drawn to scale and the no-load and the full-load saturation curves are determined and plotted. For the machine in question, the curves are given in Fig. 19.

(d) **Design of the shunt coils.** The details are as follows:

The no-load excitation = 9,990 ampere-turns per pole, Fig. 19, or Par. 82.

E_f, the volts per coil, equals $0.8\times240/10$ = 19 volts; this leaves 20 per cent. of the terminal voltage to be absorbed by the field rheostat.

M, the mean turn, equals 53 in. The external periphery equals 61 in.

The size of wire equals $9{,}990\times53/19$, from Par. 85, or 28,000 cir. mils. The proper size of wire is No. 5.5 A.W.G., a special size between Nos. 5 and 6, which has a section of 29,500 cir. mils and a diameter when insulated with double cotton of 0.19 in. When such odd sizes are not available, the coil can be made with the proper number of turns of No. 5 wire in series with the proper number of turns of No. 6, so as to have a field coil of the proper resistance.

The number of layers of wire in a 2-in. depth equals $2/0.19$ = 10.

The number of turns per layer in a 10-in. length equals $10/0.19$ = 53.

s_f, the number of turns per coil, equals 530.

I_f, the shunt current, equals $9{,}990/530$ = 18.8 amp.

The current density equals $29{,}500/18.8$ = 1,570 cir. mils per amp.

(e) **Design of the series coils.** The details are as follows:

Excitation at full load and normal voltage	= 13,400 ampere-turns, Fig. 19.
Shunt excitation at normal load	= 9,990 ampere-turns.
Series ampere-turns per pole at full load	= 3,410
Series turns per pole	= 2.5
Series current = $3{,}410/2.5$	= 1,370 amp.
Current in series shunt	= 300 amp.

The current density is taken 20 per cent. greater than in shunt coils because the series coils are better ventilated.

Current density	= 1,300 cir. mils per amp.
Size of wire = $1{,}300\times1{,}370$	= 1,780,000 cir. mils = 1.4 sq. in.
Resistance of 2.5 turns	= 7.4×10^{-6} ohms.
Loss in one series coil	= $1{,}370^2\times7.4\times10^{-6}$ = 140 watts.

The permissible watts per sq. in. is taken 20 per cent. greater than in shunt coils.

Watts per sq. in.	= 0.72
Necessary radiating surface	= 140/0.72 = 195 sq. in.
Length L_f of series coil	= 195/61 = 3.2 in.
Depth of wire = wire section/L_f	= 0.45 in.

Size of wire = 3 strips (3.2 in. × 0.15 in.).

GENERAL DESIGN AND CONSTRUCTION

90. Type of construction for small machines. Fig. 45 shows the type of construction generally adopted for machines up to 100 h.p. at 600 rev. per min.

91. The armature core (M in Fig. 45) is built of laminations of sheet steel 14 mils (0.35 mm.) thick, which are separated from one another by layers of varnish and have slots F punched to carry the armature coils G.

92. A marking notch is punched at one side of the key-way K (Fig. 45) and these notches must line up when the punchings are assembled, to ensure that the burrs at the edges all lie in the same direction.

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93. Brass vent segments (*P* in Fig. 45), about ¼ in. (1 cm.) wide, separate the core into sections about 3 in. (7.5 cm.) wide. The core and the vent segments are clamped between end heads *N* which carry coil supports *L* attached by arms shaped like fans. The coils are held in place against centrifugal force by steel band wires.

94. The poles (*B* in Fig. 45), are of circular cross-section in order to give the required area for the magnetic flux with the minimum length of mean turn of field coil *A*. They are made of forged steel and have laminated pole faces *E* made of sheet steel 25 mils (0.63 mm.) thick.

95. End play is provided for by making the axial length of the pole face ¼ in. (1 cm.) shorter than that of the armature core. This enables the revolving part of the machine to oscillate axially and so prevent the journals, bearings and commutator from wearing in grooves.

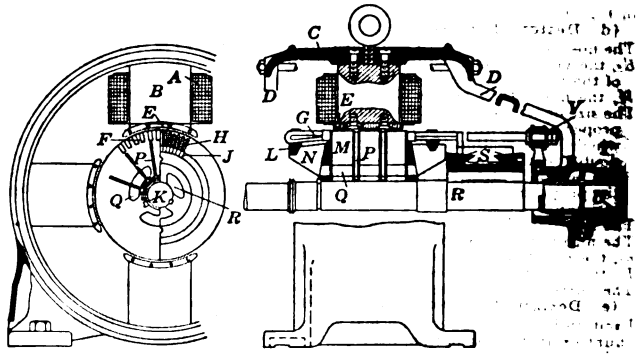


FIG. 45.—Small direct-current motor.

96. The yoke (*C* in Fig. 45) carries the bearing housings *D* which stiffen the whole machine. The housings can be rotated with respect to the yoke through 90 deg. or 180 deg., so that the machine may be mounted either on a wall or a ceiling. This rotation of the bearings is necessary because the machine is lubricated by **oil rings** and the **oil wells** must always be below the shaft.

97. The commutator segments (*J* in Fig. 45) are of hard-drawn copper and have a wearing depth of from 0.5 in. (1.25 cm.) on a 5-in. (12.5-cm.) commutator to 1.0 in. (2.5 cm.) on a 50-in. (125-cm.) commutator. The commutator shell, as the clamps and their supports are called, is provided with air passages *R* which help to keep the machine cool.

98. The bearing construction is shown in detail in Fig. 45. The projection *T* on the oil-hole cover keeps the oil ring from rising and resting on the bushing; the oil slingers prevent the oil from creeping along the shaft. The liner of special bearing metal is given a snug fit in the bearing shell, and can be removed when worn and another put in its place. A small overflow at *U* makes it impossible to fill the bearing too full.

99. The brushes are carried on studs which are insulated from the rocker arm *V*. The rocker arm is carried on a turned seat on the bearing and can be clamped in a definite position.

100. Type of construction for large engine-type generators. For large direct-connected engine-type units the type of construction shown in Fig. 46 is generally adopted. The **armature core** is built of segments carried by dovetails on the spider. The segments of alternate layers overlap so as to break joints and give a solid core. The **poles** are of rectangular cross-section

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and are built of laminations 25 mils (0.63 mm.) thick, of the shape shown at *P*, and assembled so that the rounded pole tips point in opposite directions and a saturated tip is produced which helps commutation. The **shaft, base and bearings** are generally supplied by the engine builder, so that the commutator must be supported from the armature spider; the **brush rigging** must also be supported by the machine.

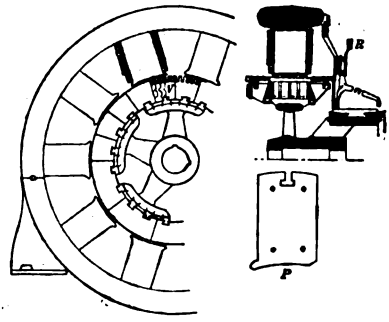


FIG. 46.—Large engine-type generator.

101. Mechanical design.* The **yoke** should be heavy and, in engine-type units, is often made with a large section of cast iron rather than a smaller section of cast steel; it must be stiff enough to prevent undue sagging even when there is a large unbalanced magnetic pull. The **shaft** should be stiff enough to limit the deflection to 5 per cent. of the air-gap clearance and, along with the **spider**, should have a **factor of safety** of 12 to take care of short-circuits.

102. Unbalanced magnetic pull.† If the armature of a machine is x cm. out of centre, the flux density under the poles where the gaps are smallest will be greater than under the poles where the gaps are largest, and the pull on one side of the machine will be greater than on the other by an amount

$$kS\mathfrak{G}^2\frac{x}{\delta} \qquad (23)$$

where $\mathfrak{G}$ is the effective gap density,

$S = \pi D_a L_e$, the total armature-core surface,

x = armature displacement,

δ = length of air-gap,

$k = \dfrac{1}{7.2\times10^7}$ if inch units are used and the pull is in pounds,

$k = \dfrac{1}{2.47\times10^7}$ if centimeter units are used and the pull is in kilograms.

The above formula holds for a two-circuit winding; if a multiple winding is used, the e.m.fs. in the different paths will be unequal, and circulating currents will flow tending to keep the flux densities under the poles equal.

INSULATION

103. General requirements. A good insulator for electrical machinery must have high dielectric strength and high electrical resistance, should be tough and flexible, and should not be affected by heat, vibration, or other operating conditions.

104. The insulating materials generally used for revolving machinery are as follows:

(a) **Micanite**, which is easily bruised and should be protected by a tougher material.

(b) **Varnished cloth**, which must be carefully handled to prevent cracking or scraping of the varnish film.

(c) **Paper**, which is chosen for its toughness and should be baked dry when tested.

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* Livingstone, "Mechanical Design and Construction of Commutators;" Livingstone, "Mechanical Design and Construction of Generators;" Hawkins and Wallis, "The Dynamo;" Hobart and Ellis, "Armature Construction."

† Behrend, B. A. *Trans.* A. I. E. E., Vol. XVII, p. 617; and Rosenberg, "Magnetic Pull in Electrical Machines," *Proc.* A. I. E. E., Vol. 37, p. 1069.

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(d) **Cotton tape**, which is used to insulate copper strip of large section.

(e) **Cotton covering** is used in one, two or three layers, and has the thickness given in Sec. 5, when applied to round wire. Small strip copper is generally double-cotton-covered, and the total thickness of insulation (two sides) varies from about 14 mils on the smaller sizes to about 20 mils on sizes more than ¼ in. thick.

(f) **Impregnating compound** must be used at a temperature lower than 120 deg. cent., which is the breakdown temperature of cotton. It should have as little chemical action as possible on copper, iron and insulating materials.

(g) **Elastic finishing varnish** should have a hard skin when dry and should be proof against oil, water, acids, and alkalies.

105. The limiting temperature* for cellulose materials is about 120 deg. cent., but the operating temperature should not exceed about 90 deg. cent. When subjected to higher temperatures for long periods, the material becomes dry and brittle, and pulverizes under vibration. When mica, asbestos, enamels and special gums can be prepared in such a manner that they are tough and flexible and do not become brittle at high temperatures, then the operating temperature limit may be increased.

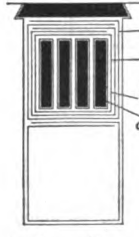


FIG. 47.

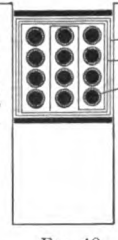


FIG. 48.

FIGS. 47 AND 48.—Armature slot insulation.

106. Insulation of adjacent conductors in a slot. The voltage between adjacent commutator segments seldom exceeds 20 volts, so that cotton tape is sufficient insulation between adjacent coils in a slot. When the individual coils are made of a number of turns of round double-cotton-covered wire, it is advisable to put extra insulation between them as shown in Fig. 48, because the cotton covering may become damaged when the coils are squeezed together to get them into a slot.

107. Example of 240-volt armature insulation. The winding is to be of the double-layer multiple type with two turns per coil and four coils or eight conductors per slot. The conductors are to be of strip copper wound on edge. A section through the slot and insulation is shown in Fig. 47, and the various operations are as follows:

(*a*) After the copper has been bent to shape, tape it all over with one layer of half-lapped cotton tape 6 mils (0.15 mm.) thick. This forms the insulation between adjacent conductors in the same slot.

(*b*) Tape together the two coils that form one group, with one layer of half-lapped cotton tape 6 mils (0.15 mm.) thick. This forms the end-connection insulation and also part of the slot insulation.

(*c*) Bake the coil in a vacuum tank at 100 deg. cent. so as to expel all moisture, then dip it in a tank of impregnating compound at 120 deg. cent. and leave it there long enough to become saturated with compound.

(*d*) Place one turn of empire cloth 10 mils (0.25 mm.) thick on the slot portion of the coil and lap it over as shown at *d*. This empire cloth coil should project 0.75 in. (2 cm.) from each end of the core.

(*e*) Place one turn of paper 10 mils (0.25 mm.) thick on the slot-portion of the coil and lap it over as shown at *e*. This paper also should project 0.75 in. (2 cm.) beyond the core at each end. It is not placed on the coil for insulating purposes, but to protect the other insulation which is likely otherwise to become damaged when the coils are being placed in the slots.

(*f*) Heat the coil to 100 deg. cent. and then press the slot portion to shape while hot. The heat softens the compound and the pressure forces out the excess of compound. The coil is allowed to cool under pressure and comes out of the press with such a shape and size that it slips easily into the slot.

(*g*) Dip the ends of the coil into elastic finishing varnish.

*Rayner. *Journal* of Inst. of Elec. Eng., Vol. XXXIV, p. 613.

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106. Example of 550-volt insulation for a railway motor armature. The winding is of the double-layer, two-circuit type with four turns per coil of double-cotton-covered wire and six coils or twenty-four conductors per slot. A cross-section through the slot and insulation is shown in Fig. 48. The various operations are as follows:

(*a*) The cotton-covered wire is treated with enamel to increase its heat-resisting properties and is then bent to shape.

(*b*) A group of three coils are placed together and a wrapping of mica cloth, made of 5-mil (0.13-mm.) mica and 5-mil (0.13-mm.) cloth is placed on the slot portion of the coil to form the insulation between coils and also between the coil group and the sides of the slot.

(*c*) The end leads of each coil have to pass all the other turns of the coil and are insulated with a stocking of cotton, different colors being used for the three coils in a group so that the position of each coil may be easily determined when the winding is being connected to the commutator.

(*d*) The group of three coils is taped on the ends with half-lapped cotton tape 6 mils (0.15 mm.) thick, which tape is allowed to overlap the slot insulation for 0.5 in. (1.3 cm.) so as to bind it in place.

(*e*) The group of coils is completely taped with one layer of half-lapped cotton tape 6 mils (0.15 mm.) thick.

(*f*) The top and the bottom layers of the winding are separated from one another at the ends by a layer of canvas 30 mils (0.75 mm.) thick and in the slot by a layer of fibre 30 mils (0.75 mm.) thick.

(*g*) After being wound, the armature is impregnated with compound and is finally painted with elastic finishing varnish.

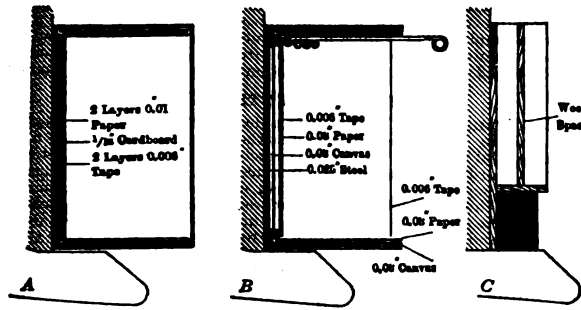


FIG. 49.—Field coil insulation.

109. Field coil insulation. Three examples are shown in Fig. 49. The coils, after being wound and taped, are baked in a vacuum tank and then impregnated with compound. This compound is a better insulator than the air which it replaces; it is also a better conductor of heat.

110. Ventilated field coils, as shown at *C* in Fig. 49, are insulated with wooden spacing pieces about 0.5 in. (1.3 cm.) thick. The coils are made self-supporting by being impregnated with solid compound at about 120 deg. cent. The insulation on the individual turns of the series coil consists of one layer of half-lapped cotton tape 6 mils (0.15 mm.) thick.

111. Fire-proof field coils for railway motors have been made with strip copper wound on edge, with asbestos insulation between layers. The coils are brought to a red heat to expel the binding material in the asbestos fabric and then placed in a metal case lined with asbestos and sheet mica.

112. Commutator segments are insulated from one another by micanite about 30 mils (0.75 mm.) thick, strips of uniform thickness being used and the copper segments tapered to suit. The mica must be one of the soft varieties (Sec. 4) so that it will wear equally with the copper segments.

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The segments of copper and mica are assembled together in an external press ring, are next heated to soften the binding material in the micanite, and are then drawn tightly together. The *V*-grooves shown in Fig. 45 are then turned and the segments clamped tightly by the *V*-cones, from which they are insulated by mica cones $\frac{1}{16}$ in. (1.6 mm.) thick.

113. Potential stresses due to switching. A conductor conveying a current is surrounded by a magnetic field. If the circuit be suddenly opened, the flux decreases rapidly and an e.m.f. is induced in the circuit. In the case of shunt field coils with many turns, this e.m.f. may be excessive and must be provided against as described in Par. **245** and **249**. This flux due to the field coils also threads the armature, and the sudden change of flux may increase the e.m.f. per coil enough to cause flashing over between segments or to break down the insulation between adjacent coils in the same slot. This latter trouble may also be caused by a sudden change of load (see Par. **57**).

114. If, due to switching, any point in a coil be suddenly raised by a potential of E volts, the potential of the whole winding will gradually rise; but, as this requires a definite though very short interval, the potential difference across the first few turns of the coil is approximately equal to E and may be large enough to break down the insulation between adjacent turns near the terminals.

115. Puncture test. To make sure that there is enough insulation between the conductors and the core, and that this insulation has not been damaged in handling, all new machines are subjected to a puncture test before they are shipped, that is, a high voltage is applied between the conductors and the core for 1 min. If the insulation does not break down, it is assumed to be ample. The values of puncture voltage recommended by the Standards Committee of the American Institute of Electrical Engineers may be found in Sec. 24. For further information on insulation see footnote.*

COOLING AND VENTILATION

116. Heat transfers. The losses in an electrical machine are transformed into heat, causing a rise of temperature at the source of loss. Heat is transmitted in general by three methods, namely, conduction, convection and radiation. In order that a flow of heat may take place, there must be a difference of temperature, and heat flows in the direction of diminishing temperature. Thus the highest temperature, or "hot spot," in an electrical machine, is at the seat of loss; the temperature falls in the direction in which the heat flows, and becomes a minimum at the point or points where the heat leaves the machine. The temperature becomes stationary when the rate at which heat is generated is equal to the rate at which it is conducted away.

117. Heating and cooling curves. The rate at which heat is dissipated depends on the difference between the temperature of the machine and that of the surrounding air. During a brief interval after starting under load, this temperature difference is small, very little heat is dissipated, and the temperature rises rapidly. As the temperature increases, more of the heat is dissipated, and the temperature rises more slowly. The heating and cooling curves of a continuous-current motor are given in Fig. 50, the cooling curve being the reciprocal of the heating curve.

118. General effect of densities and speed. The lower the flux and the current densities, the larger will be the mass of material in the machine for a given loss, and the longer the time taken to reach the final temperature. Slow-speed machines are poorly ventilated, have low current densities, and require a long time to reach the final temperature; field coils require longer than armature coils because they are stationary and the current density in the wire is very low.

119. Permissible temperature rise. Cotton insulation should not be operated continuously at temperatures greater than about 90 deg. cent. This permits a temperature rise of 50 deg. cent. with an air temperature of 40 deg. cent.

* Fleming and Johnson, *Journal* of Inst. of Elec. Eng., Vol. XLVII, p. 530; Hobart and Turner, "Insulation of Electric Machines;" Rayner, *Journal* of Inst. of Elec. Eng., Vol. XXXIV, p. 613; Vol. XLIX, p. 3.

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120. Intermittent ratings. Suppose that a machine is operating on a continuous cycle, x min. loaded and y min. without load. The temperature of the machine will vary during each cycle between the values θ_x and θ_y (Fig. 50), where the temperature increase in the interval x is equal to the temperature decrease in the interval y. Under these service conditions, θ_h, the highest operating temperature, is less than θ_m, the maximum temperature that would be obtained on continuous operation under load. For this service, therefore, a machine may be designed with higher copper and iron densities than otherwise it would have if designed for the same load but for continuous operation. It must be noted that, if the machine is stationary during the period of no load, the drop in temperature is small, and the rating of the machine cannot be made much greater than if it were operating on continuous load.

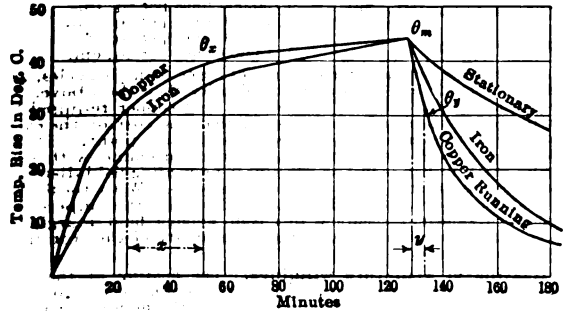


FIG. 50.—Heating and cooling curves of a direct-current motor.

121. Heat conduction in the armature core. The hottest part of the core is at A, Fig. 51; consequently the heat has to be conducted along the laminations and dissipated from surfaces B, and also across the laminations and layers of varnish and dissipated from surfaces C. The conductivity along the laminations is about fifty times that across the laminations, but the end surface of the laminations is small compared with the surface of the vent ducts, so that **radial ducts** are effective and necessary.

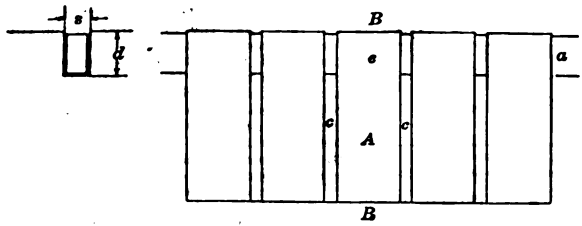


FIG. 51.—Heat conduction in armature core.

122. Flux density and peripheral velocity. The peripheral velocity of a machine in ft. per min. is

$$v = 10 \times \text{pole pitch in inches} \times \text{frequency in cycles per sec.}$$

Hence for a given frequency, the peripheral velocity of the machine is proportional to its pole pitch. The flux in the armature core of a direct-current machine is always alternating, and the **frequency** is equal to the product of the revolutions per sec. and the number of pairs of poles (interpoles excluded).

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The core length being fixed, the longer the pole pitch the greater will be the flux per pole and the deeper the core required to carry this flux. When the peripheral velocity is high, the core is therefore deep and the vent ducts have a large surface and are very effective, so that the ventilation is good. The loss, however, is large since much iron is used in the core. When the peripheral velocity is low, the core is shallow and the vent ducts are not very effective because of their small surface, and the ventilation is poor; the loss, however, is small because there is not much iron in the core. It is found that, for a given frequency, the same flux densities can be used for all peripheral velocities.

123. Tooth and core densities. For frequencies up to 60 cycles per sec. and for a temperature rise of less than 50 deg. cent., the following flux densities may be used:

Actual maximum tooth density	150,000 lines per sq. in. 23,000 lines per sq. cm.
Average core density	85,000 lines per sq. in. 13,000 lines per sq. cm.

Higher densities may be used for frequencies lower than 60 cycles, as far as heating is concerned; but, with a greater density than the above, the core becomes saturated and the cost of the extra field copper required to send the flux through a saturated core is greater than the cost of the extra iron required to keep the flux density below the saturation point. There is no such objection to high tooth densities, because a machine with saturated teeth and a short air-gap is just as effective in preventing field distortion as a machine with unsaturated teeth and a long air-gap. With tooth densities greater than the above, it is difficult to predetermine the ampere-turns for the teeth with sufficient accuracy to ensure enough field margin to give normal voltage at full load, because the permeability of the iron used may be lower than was expected.

124. Heating of armature windings. The heating of the end connections must be considered separately from the heating of the core, because the kind of radiating surface is different, and also the manner in which it is cooled. The temperature rise is proportional to

$$\frac{\text{ampere-conductors per in. of periphery}}{\text{cir. mils per amp.}} \qquad (24)$$

and may be obtained from Fig. 52. For a given loss per unit area of radiating surface, a large machine operates at a lower temperature than a small one because its windings are not so crowded on the ends, and free passage of air into the machine is not restricted by the bearing housings.

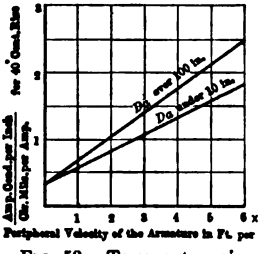


FIG. 52.—Temperature rise of armature coils.

125. Overload temperatures. Due to the fact that the heat loss in the copper has to pass through the insulation or be dissipated from the end connections, the maximum rise in temperature of a machine will be more nearly proportional to the copper loss than to the total loss in armature core and copper. A large number of tests on standard machines have shown that the temperature rise of an armature is approximately proportional to the sum of the armature copper loss plus 30 per cent. of the iron loss.

126. Temperature gradient in the conductors.* The hottest part of the winding is at e, Fig. 51. If it be assumed that all the heat is conducted along the copper and dissipated from the ends, then the difference in temperature between e and a in deg. cent. is given by the formula.†

* Goldschmidt, *Electrotechnische Zeitschrift*, Vol. XXIX, p. 886; Gray, "Electrical Machine Design;" Symons and Walker, *Journal* of Inst. of Elec. Eng., Vol. XLVIII, p. 674.

† Gray. "Electrical Machine Design," p. 110.

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$$\frac{5.7\times10^4\times(\text{length } ae \text{ in inches})^2}{(\text{cir. mils per amp.})^2} \quad \text{(deg. cent.)} \qquad (25)$$

If ae is 10 in., and the number of cir. mils per amp. is 500, then this temperature difference is 23 deg. cent.

Much of the heat, however, is conducted through the insulation and, assuming that all the heat travels in this direction, the temperature difference between the copper and the surrounding iron, in deg. C., is given by the formula

$$\frac{1}{0.003}\left(\frac{\text{ampere-conductors per slot}}{\text{cir. mils per amp.}}\right)\times\left(\frac{\text{thickness of insul.}}{2d+s}\right) \qquad (26)$$

In the machine shown in **Fig. 35**, the design data is as follows:

Ampere-conductors per in.	= 730
Slot pitch	= 0.91 in.
Ampere-conductors per slot	= 670
Cir. mils per amp.	= 560
$2d+s$	= 3.63 in., Fig. 51
Thickness of insulation	= 0.06 in. including clearance
Temperature difference	= 6.5 deg. cent.

127. Commutator heating. The direction of the air circulation in a commutator with open necks is shown in Fig. 53, and the temperature rise may be obtained from the heating curve. The radiating surface is taken as $\pi D_c F$. The effect of the necks has not yet been determined experimentally. Part of the neck from a to b can be closed up without affecting the ventilation or the temperature rise to any great extent. The losses are assumed to be brush friction and contact resistance losses; hence if the commutation is poor and the brushes chatter badly the temperature rise may be higher than that obtained from the curve.

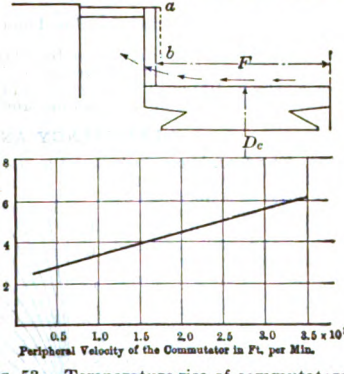


FIG. 53.—Temperature rise of commutators.

128. Field coil heating. The temperature rise of the coil surface is proportional to the loss per unit area of external surface and may be obtained from **Fig. 44** if B, Fig. 42, is taken as the radiating surface. The effect of armature fanning can readily be understood; a short coil is more effective than a long one because of the larger per cent. of the loss that is dissipated from the ends of the coil. Ventilating openings, as shown in C, Fig. 49, allow the loss per unit area of external surface to be 50 per cent. greater than for an unventilated coil.

129. The maximum temperature* of the coil is that which limits the current it can carry, but this temperature cannot readily be determined experimentally. **The external surface temperature** may be measured by a thermometer and the **mean temperature** can be found by the increase in resistance of the coil. The resistance at any temperature t is approximately $R_t = R_o(1+0.004t)$, where R_o is the resistance at 0 deg. cent., and t is expressed in deg. cent. The ratio between the maximum and the mean temperatures seldom exceeds 1.2, but the ratio between the mean and the external surface temperatures may have any value from 1.4 to 3 depending on the thickness of the coil and the amount of insulation used, an average value for coils 2 in. thick, made of double-cotton-covered wire and impregnated, is 1.5 when no external protecting covering is used.

* Lister. *Journal* of Inst. of Elec. Eng., Vol. XXXVIII, p. 399.

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130. Semi-enclosed machines have the frame openings screened with perforated sheet metal. This prevents free circulation of air through the machine and causes the temperature to rise, on an average, about 20 per cent. higher than if operating as an open machine.

131. In totally enclosed machines, the temperature rise of the core and the coils is proportional to the total loss in the machine (neglecting bearing friction); it is independent of the distribution of this loss and may be found from Fig. 54. The rating as an enclosed machine will be considerably lower than that as an open machine. A casing around the machine makes it equivalent to an enclosed machine with an extra large radiating surface; the casing should be of heat-conducting material such as sheet metal and should not be of wood. Fans on the armature help in the cooling of enclosed machines by blowing the hot air against the casing.

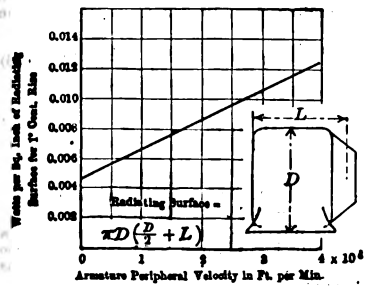


FIG. 54.—Temperature rise of enclosed motors.

132. Forced ventilation,* whereby air is blown through a machine by an external fan or by a fan attached to the armature, allows the machine to have the same rating as it would have when operating as an open machine; 100 cu. ft. (2.8 cu. m.) of air per kw. loss should be supplied for a temperature rise of the windings and the core of 40 deg. cent.

EFFICIENCY AND LOSSES

133. The iron losses† consist of hysteresis and eddy-current losses in the armature teeth and core; these may be kept small by the use of special grades of iron (Sec. 4) and by the use of thin and well-varnished laminations. There are losses also in the end heads and spider due to leakage flux; losses due to filing of the slots which short-circuits the laminations; losses due to the fact that the core flux takes the shortest path and crowds in behind the teeth, so that the core density is not uniform; and pole-face losses‡ due to the movement of the armature teeth past the faces of the poles. In order to minimize the pole-face losses, the pole faces should be laminated if the slot opening is greater than twice the air-gap clearance.

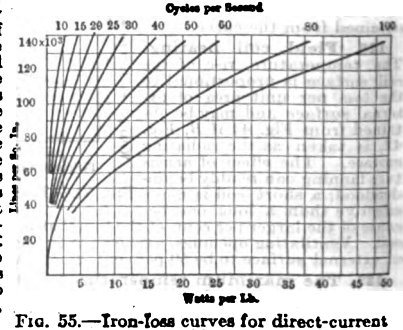


FIG. 55.—Iron-loss curves for direct-current machines.

134. The iron losses increase with the load if the flux per pole is kept

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*Gray. "Heating of Pipe-ventilated Machines," London Electrician, Jan. 16, 1914.

†Thornton. "Distribution of Magnetic Induction in Armatures," *Journal* of Inst. of Elec. Eng., Vol. XXXVII, p. 125.

‡Wall and Smith. "Pole-face losses," *Journal* of Inst. of Elec. Eng., Vol. XL, p. 577.

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constant, because of field distortion, as the densities are then very high under alternate pole tips.

135. The individual iron losses cannot be calculated separately, and curves such as those in Fig. 55, obtained by tests on completed machines, must be used as follows:

Taking the machine shown in Fig. 35:

Actual maximum tooth density	= 150,000 lines per sq. in.
Average core density	= 84,000 lines per sq. in.
Weight of armature teeth	= 385 lb.
Weight of armature core	= 2,300 lb.
Frequency = $p \times$ r.p.m./120	= 16.6 cycles per sec.
Tooth loss per lb.	= 6 watts, from Fig. 55.
Core-loss per lb.	= 1.8 watts.
Total iron loss = $(385 \times 6) + (2{,}300 \times 1.8)$	= 6,450 watts.

136. The armature copper loss is given by the formula

$$\frac{ZLI_a^2}{\text{c.m.}} \qquad \text{(watts)} \qquad (27)$$

where Z is the number of conductors, L is the length of one conductor in in. (Fig. 56), I_a is the current in each conductor, or the total current divided by the number of armature paths, and c.m. is the cross-section of each conductor in cir. mils.

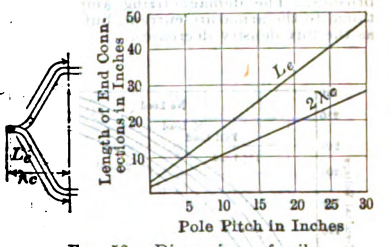


FIG. 56.—Dimensions of coils.

137. The shunt excitation loss equals $E_t I_f$ watts, where E_t is the terminal voltage and I_f the shunt current. In a generator, about 20 per cent. of this loss will be in the shunt-field rheostat.

138. The series excitation loss equals $I_a^2 R_s$ watts, where I_a is the total current in the machine and R_s is the combined parallel resistance of the series field coils and the series shunt.

139. The brush contact resistance loss has been discussed in Par. 38 and equals $E_b I_a$ watts, where E_b is the voltage drop per pair of brushes and I_a is the total current of the machine.

140. The bearing friction loss for moderate-speed bearings with ring lubrication and light machine oil is given by the formula

$$0.8dl\left(\frac{v}{100}\right)^{\frac{3}{2}} \qquad \text{(watts)} \qquad (28)$$

where d is the bearing diameter in inches, l is the bearing length in inches, and v is the rubbing velocity in feet per min.

141. The brush friction loss, assuming the coefficient of friction to be 0.28 and the brush pressure to be 2 lb. per sq. in., is given by the formula

$$1.25\,A\frac{V}{100} \qquad \text{(watts)} \qquad (29)$$

where A is the total brush rubbing surface in square inches, and V is the rubbing velocity in feet per min. The brush pressure is generally less than 2 lb. per sq. in. (0.14 kg. per sq. cm.) except for railway motors, where it may be twice as large in order to keep the contact firm in spite of the vibration of the machine.

142. The windage loss cannot be accurately calculated and, with peripheral velocities less than 6,000 ft. per min., is so small that it may be neglected.

143. The efficiency of a generator is given by the expression

$$Eff_c = \frac{\text{output}}{\text{output} + \text{losses}} \qquad (30)$$

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The efficiency of a motor is expressed

$$Eff_m = \frac{\text{input} - \text{losses}}{\text{input}} \tag{31}$$

When the copper losses only are taken, the result is the **electrical efficiency.** The **commercial efficiency,** which is the important one, is obtained by substituting the total losses in the above equations. For values see Figs. 66 and 67.

GENERATOR CHARACTERISTICS AND REGULATION

144. External characteristics of separately excited generators. Fig. 57 shows some of the saturation curves of a continuous current generator. Given a constant excitation of 18 amp., the terminal voltage at no load is 320, at full load is 292, and at twice full load is 262 volts. The relation between E_t, the terminal voltage, and I_a, the load current, is given in curve 1, Fig. 58, the excitation and the speed being constant. This curve is called the external characteristic of the machine. The voltage drops as the load increases because the cross-magnetizing and the demagnetizing effects of armature reaction reduce the flux per pole, while part of the generated voltage is required to send the armature current through the armat re and brushes. The demagnetizing ampere-turns per pole are directly proportional to the armature current, but their effect in reducing the flux increases as the flux density decreases.

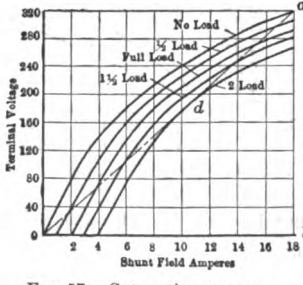


FIG. 57.—Saturation curves.

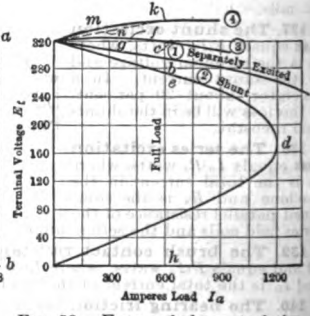


FIG. 58.—External characteristics.

145. The external characteristic of a shunt machine is plotted in curve 2, Fig. 58; the drop in voltage is greater than in a separately excited machine because, since the field-coil resistance is constant, the exciting current in the shunt coils decreases as E_t decreases. The points for this characteristic curve are obtained as follows: the dotted straight line in Fig. 57 is drawn through the point a, where $ab/ob = 320/18 = 17.8$ ohms, the latter being the constant field resistance. With a terminal voltage of 320 and the corresponding shunt current of 18 amp., the load current is zero. With a terminal voltage of 272 and the corresponding shunt current of 15.3 amp., full-load current is required to give the proper armature reaction. As the resistance of the external circuit is reduced the armature current increases and the terminal voltage decreases until point d is reached, after which a further reduction in external resistance causes such a large drop in voltage that the load current decreases. For example, with a terminal voltage of 63 and the corresponding shunt current of 3.55 amp., full-load armature current is sufficient to give the proper armature reaction.

146. Critical resistance of shunt generators. The external resistance equals E_t/I_a, and may be found from curve 2, Fig. 58. Using the value so found, the relation between terminal voltage and external resistance, and also that between current and external resistance, are plotted in Fig. 59. The critical resistance is 0.1 ohms; whenever the external resist-

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ance is reduced below this value, the machine becomes completely demagnetised (except for the residual magnetism), and the terminal voltage and the armature current both become practically zero.

147. **When a shunt generator is short-circuited** the machine is demagnetized and the current becomes negligible (Fig. 59). At the instant of short-circuit, however, the flux in the pole cannot reduce suddenly to zero, and the voltage due to this flux will send a large current through the circuit; at the end of a few seconds, however, the current will have become zero.

148. **Instability of unsaturated shunt generators.** If the no-load, normal voltage point on the saturation curve is a, Fig. 60, below the point of saturation, then the overload capacity of the machine will be small, and the change of voltage with load will be large. Furthermore, a slight decrease in speed will cause a decrease in the generated voltage, which will decrease the shunt field current and cause the voltage to drop still further. If ac is tangent to the saturation curve at point a, then the ratio of voltage change to the change of speed producing it, is ab/oc.

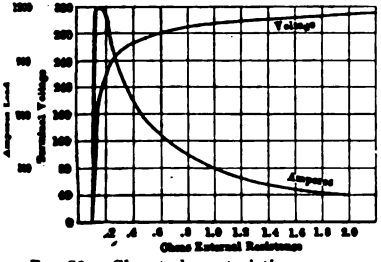


FIG. 59.—Shunt characteristics on a resistance base.

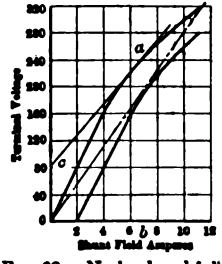


FIG. 60.—No-load and full-load saturation curves.

149. **The regulation** of electrical machinery is defined in the A. I. E. E. Standardization Rules (Sec. 24). The **voltage regulation** of a separately excited generator is bc/bk (Fig. 58); for a shunt generator it is ec/ek (Fig. 58); for a flat-compounded generator it is fg/ch; and for an overcompounded generator it is mn/hk (Fig. 58). The **current regulation** of a constant-current generator depends largely on the type of regulator used and is defined as the ratio of the maximum difference of current from the rated load value (occurring within the range from rated load to short-circuit, or minimum limit of operation) to the rated load current.

150. **To maintain the terminal voltage constant,** shunt generators may be operated with an adjustable resistance in series with the shunt field coils; this resistance may be reduced automatically, or by hand, as the load increases. Automatic regulators for this purpose generally consist of a solenoid connected across the terminals of the machine, acting as a relay which will open or close an operating circuit and vary the resistance of the field circuit as required.

151. **The Tirrill Regulator,** described in Sec. 10, periodically short-circuits part of the field rheostat by means of light vibrating contacts of small inertia; the time during which the rheostat is short-circuited or is active determines the average field current and therefore the voltage of the machine.

152. **Compound machines,** operated without a regulator, keep the voltage approximately constant from no load to full load because, due to the series field coils, the total excitation increases with the load; the machine is then said to be **flat-compounded.** By the use of an extra strong series field, the voltage may be made to increase with the load; the machine is then said to be **overcompounded.** Curves 3 and 4, Fig. 58, show the

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characteristic curves for compound generators. The compounding of a machine may be reduced by shunting the series field coils with a resistance; this resistance is called a "series shunt."

153. Series generators. Curve 1, Fig. 61, shows the relation between voltage and current if there is no armature resistance or armature reaction. This is really the no-load saturation curve of the machine and is determined by separately exciting the field coils so that no current flows in the armature. Curve 2 shows the actual relation between terminal voltage and load current.

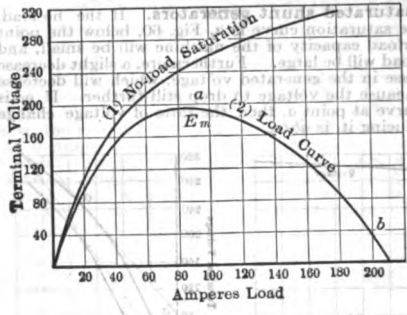


FIG. 61.

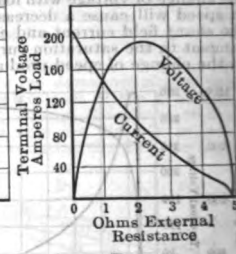


FIG. 62.

FIGS. 61 AND 62.—Characteristic curves of a series generator.

The total voltage drop consists of that portion due to the decrease in flux caused by armature reaction, and that required to send the current through the armature, brushes and series field coils.

154. Critical resistance of series generators. The values of current in a series generator and the resistance of the external circuit are plotted in Fig. 62. The critical resistance of the machine is 4.9 ohms; with an external resistance greater than this, the machine will not excite, or build up.

155. Series machines were formerly used as **constant-current generators** for the operation of **arc lamps** in series, but few of them are now in service. Specially designed machines were operated with automatic regulators so as to have the line *ab* (Fig. 61) nearly vertical, and the current practically constant for all voltages up to E_m (Fig. 61).

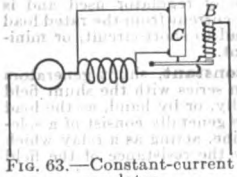


FIG. 63.—Constant-current regulator.

156. The Brush regulator, shown diagrammatically in Fig. 63, has been used as a **constant-current regulator.** The carbon pile *C* has the property that its resistance decreases through a wide range as the pressure between the ends increases. If the current in the external circuit increases, the pull of the solenoid *B* also increases, and the carbon pile is compressed and its resistance reduced so that it shunts more of the current from the series field coils; the flux in the machine is therefore reduced and the voltage drops until the current reaches the value for which the regulator was set. Other types of constant-current regulators are described in Par. **209** and **212.**

MOTOR CHARACTERISTICS AND REGULATION

157. Counter e.m.f. It was pointed out in Par. **6** that, since a motor armature revolves in a magnetic field, an e.m.f. is generated in the conductors which is opposed to the direction of the current and is called the counter e.m.f. The applied e.m.f. must be large enough to overcome the counter

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e.m.f. and also to send the armature current I_a through R_m, the resistance of the armature winding, the brushes and the series field coils; or

$$E_a = E_b + I_a R_m \quad \text{(volts)} \quad (32)$$

where E_a is the applied e.m.f. and E_b, the counter e.m.f., is given by Eq. 9, Par. 60.

156. Shifting of the brushes. It may be seen from Fig. 2 that, while the brushes of a generator are shifted forward in the direction of motion to help commutation, those of a motor have to be shifted backward. In each case, however, the armature reaction reduces the flux per pole.

159. The torque equation. The torque of a motor is proportional to the number of conductors on the armature, to the current per conductor and to the total flux in the machine. The formula for the torque is

$$\text{torque} = 0.1175\, Z\, \phi I_a \left(\frac{\text{poles}}{\text{paths}}\right) 10^{-8} \quad \text{(lb. at 1 ft. rad.)} \quad (33)$$

where Z is the total number of armature conductors, ϕ is the total flux per pole, and I_a is the armature current taken from the line.

160. The speed equation is

$$E_b = E_a - I_a R_m = Z\phi \left(\frac{\text{r.p.m.}}{60}\right) \left(\frac{\text{poles}}{\text{paths}}\right) 10^{-8} \quad \text{(volts)} \quad (34)$$

or

$$\text{r.p.m.} = 60 \left(\frac{E_a - I_a R_m}{Z\phi}\right) \left(\frac{\text{paths}}{\text{poles}}\right) 10^{8} \quad (35)$$

For a given motor the number of armature conductors Z, the number of poles, and the number of armature paths, are constant. The torque can therefore be expressed as

$$\text{torque} = \text{a constant} \times \phi I_a \quad (36)$$

and the speed, likewise, is expressed

$$\text{r.p.m.} = \text{a constant} \times \left(\frac{E_a - I_a R_m}{\phi}\right) \quad (37)$$

161. Shunt-motor speed and torque. In this case E_a, R_m and ϕ are constant, and the speed and torque curves are shown in curves 1, Fig. 64; the effective torque is less than that generated, by the torque required for the windage and the bearing and brush friction. The drop in speed from no load to full load seldom exceeds 5 per cent.; indeed, since ϕ, the flux per pole, decreases with increase of load, due to armature reaction, the speed may remain approximately constant up to full load.

162. Effect of field-coil heating on speed. The field-coil resistance increases and the exciting current decreases about 20 per cent. as the field coils increase in temperature. The flux per pole is therefore less and the speed greater when the machine is hot than when cold, unless a field rheostat is manipulated to keep the exciting current constant. The effect of change of exciting current on speed is minimized by having the magnetic circuit well saturated, so that a large change in current will produce only a small change in flux.

163. Variable-speed operation of shunt motors can best be investigated by means of Eq. 37, Par. 160. In order to increase the speed, ϕ must be reduced by inserting a resistance in series with the field coils. In order to decrease the speed below the value which it has with full field, the quantity $(E_a - I_a R_m)$ must be decreased by placing a resistance in series with the armature. The latter resistance must be able to carry the armature current, but the starting resistance must not be used for this purpose since it is designed for starting duty only, and would burn out if allowed to carry full-load current for more than a few minutes.

164. Speed control of shunt motors by armature resistance is not very satisfactory, since the speed regulation is bad. If a motor is operating with full-load current at half speed, about 50 per cent. of the applied voltage is consumed in the resistance, but if the load were decreased, so that only half of full-load current was required, then only 25 per cent. of the applied voltage would be consumed in the same external resistance, and the motor speed would increase to 75 per cent. of normal speed, unless the external

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control resistance were automatically increased with decrease of load. Due to the large voltage drop across the external resistance, the efficiency of the system is low.

165. When the speed of shunt motors is controlled by field resistance, the speed regulation and the efficiency are both good, but the commutation is generally poor because, at high speeds, the main field is weaker than normal while the armature field is unchanged, so that the field distortion is excessive and the commutating field under the pole tip consequently disappears (Par. 35). The reactance voltage also is increased (Par. 45). With standard shunt motors without interpoles, it is generally impossible to increase the speed more than 60 per cent. by field weakening without having trouble due to sparking, the output of the machine being the normal full load.

166. Speed changes of shunt motors under rapidly fluctuating loads.* When the load on a shunt motor increases slowly, the flux per pole decreases due to armature reaction, and the speed (Eq. 37, Par. 160) remains approximately constant. If, however, the load changes rapidly, the flux per pole cannot change rapidly due to the self-induction of the field coils; the machine then operates for the instant as a constant-flux machine, and the speed drops rapidly to allow the counter e.m.f. to decrease and the necessary current to flow.

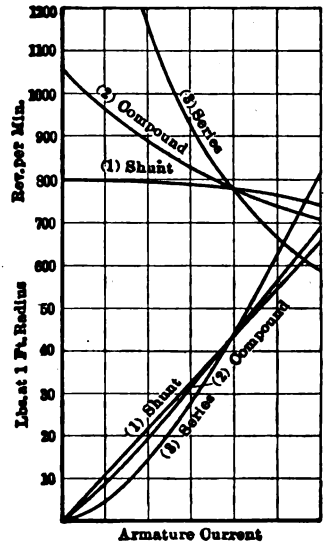


FIG. 64.—Motor characteristics.

167. Speed and torque of series motors. The speed equation (Eq. 37, Par. 160) and the torque equation (Eq. 33, Par. 159) apply to motors of all continuous-current types. In the case of series motors the flux ϕ increases with the armature current I_a; the torque would be proportional to I_a^2 were it not that the magnetic circuit becomes saturated with increase of current. Since ϕ increases with load, the speed drops as the load increases. The speed and torque characteristics are shown in curves 3, Fig. 64.

168. Excessive speeds of series motors on small loads. If the load on a series motor becomes small, the speed becomes very high, so that a series motor should always be geared or direct-connected to the load. If it were belted, and the belt broke, the motor would run away and would probably burst.

169. Speed adjustment of series motors. For a given load, and therefore for a given current, the speed of a series motor can be increased by shunting the series winding or by short-circuiting some of the series turns, so as to reduce the flux. The speed can be decreased by inserting resistance in series with the armature.

170. The compound motor is a compromise between the shunt and the series motor. Because of the series winding, which assists the shunt winding, the flux per pole increases with the load, so that the torque increases more rapidly and the speed decreases more rapidly than if the series winding was not connected, but the motor cannot run away on light loads, because of the

* Short, E. W. "Inherent Regulation of Direct-current Motor;" *Journal* of Inst. of Elec. Eng., Vol. XLVI, p. 171.

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shunt excitation. The speed and torque characteristics for such a machine are shown in curves 2, Fig. 64. The speed of a compound motor can be adjusted by armature and field rheostats, just as in the shunt machine (Par. 163).

171. **Automatic speed regulation.** To keep the speed constant under all conditions of load some kind of centrifugal governor may be used to operate on the shunt-field rheostat. A piece of apparatus of this kind now on the market* is an adaptation of the Tirrill voltage regulator, in which a centrifugal control device mounted on the motor shaft performs the functions of the main control magnet in the standard regulator. The regulator periodically short-circuits part of the shunt-field rheostat by means of light vibrating contacts of small inertia. The time during which the rheostat is short-circuited, or is active, determines the average field current and the flux per pole, and therefore the speed of the machine. When the speed is too high, the centrifugal device short-circuits the rheostat for a long period and allows the flux per pole to increase and the speed to decrease.

172. **The differential motor** is a compound-wound machine with the series winding opposing the shunt winding, so that the flux will decrease as the load increases and the speed be constant from no load to full load, or actually increase with increase of load. The series winding of such a motor should be short-circuited when starting the machine, so that the starting current will not be excessive. Differential motors are rarely used, because the speed of the shunt motor is so nearly constant from no load to full load that the extra complication of the differential winding is rarely necessary. Differential windings are used to some extent for small motors, in order to secure constant speed with variable load.

173. **Unstable operation with rising-speed characteristic.** Upon suddenly increasing the load torque on a differential motor, designed for a rising-speed characteristic, the speed for a brief instant decreases. This results in a momentary drop of counter e.m.f., which admits a larger armature current, in turn weakening the resultant field strength and further reducing the counter e.m.f. The attendant increase in armature current increases the armature torque, and the reactions are such that the latter continues to increase until it exceeds the load torque and commences to accelerate the armature. The increase in speed continues until the rising counter e.m.f. finally limits the armature current to a value at which the armature torque equals the load torque, and the speed becomes constant. These reactions, with change of load, occur quite rapidly; if, however, the field cores are large and massive, changes in flux attendant upon sudden changes in m.m.f. will lag by an appreciable time interval, on account of eddy currents in the cores. The presence of an appreciable flux lag, with very rapidly changing loads, results in unstable operation; for example, when the load is suddenly increased, the speed will drop appreciably before it commences to accelerate, and when the load is suddenly removed, the speed will rise appreciably before it commences to decrease. The effect of the armature inertia will accentuate these defects in speed regulation. Such defects are not found in motors whose speed decreases with increasing load, *i.e.*, which have a drooping speed characteristic.

174. **Interpole motors** have a commutating field which increases with the current and is not affected by armature reaction (Par. 82). Motors which are subjected to excessive overloads, and adjustable-speed motors operating at high speeds with a weak main field, give little trouble due to sparking if supplied with interpoles. **Hunting**† takes place in interpole machines which have a **rising-speed characteristic.** Such a characteristic may be obtained by working with a weak main field and with a short air-gap under the main poles, so that the field distortion under load is large and the flux per pole decreases with increase of load due to the cross-magnetising effect of the armature (Par. 82).

Such a characteristic may also be obtained by making the interpoles too strong. If commutation is perfect, the current in the short-circuited coil will be zero when that coil is in the geometrical neutral position. If, however,

* General Electric Company's Bulletin on "Automatic Voltage Regulators," 1913.

† Rosenberg, *Electrician*, Aug. 4, 1911.

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the commutating field is too strong, the reversal of this current will be advanced, so that the true neutral will be shifted backward. The flux per pole will therefore decrease with increase of load, due to the demagnetizing effect produced, and the speed will increase with load.

Due to saturation of the interpole core, the interpole field will be too strong at light loads, if of the proper strength at full load. Hunting is therefore likely to occur at light loads, particularly if the main field is so weak that the effect of the brush currents in demagnetizing the machine is proportionately large.

175. Non-inductive shunts should not be used with interpole windings if the load fluctuates rapidly, because then the current, which is rapidly changing, will pass through the shunt rather than through the interpole coils, since the latter have considerable inductance, and the commutation will therefore be poor. To make the shunt take its proper share of the current under all conditions of load, it should be made inductive by winding it on an iron core, and the ratio of the shunt reactance to the interpole-coil reactance should be equal to the ratio of the shunt resistance to the interpole-coil resistance.

176. Reversal of direction of motion. In order to reverse a motor it is necessary to reverse the current in the field coils, or in the armature, but not in both. In an interpole machine, the interpole winding must be considered as part of the armature and not as part of the field system.

WEIGHTS AND COSTS

177. Weights and costs. The cost figures given by different manufacturers on a large generator may vary as much as 50 per cent. One manufacturer may build an entirely new machine and charge part of the cost of development to the order; another may offer a standard machine of larger capacity, with a lower rating for the particular case; while still another manufacturer may increase the rating of a machine of smaller capacity, adding fans if necessary to keep the machine cool.

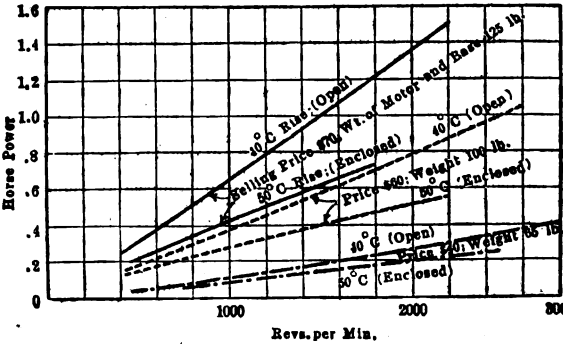


FIG. 65.—Cost of small direct-current motors without base or pulley.

The cost of large units depends largely on the cost of material, while that of small motors depends largely on the cost of labor. These costs are continually changing, so that it is impossible to give figures which are always reliable. The curves in Figs. 65, 66 and 67 are average figures for standard machines.

178. Short-time ratings. The effect of time on the rating may be seen from the following. A given frame will have a rating of 12 h.p. at 500 r.p.m. as an enclosed machine on continuous duty; or 19 h.p. at 500 r.p.m. as an open machine on continuous duty; or 31 h.p. at 500 r.p.m. with a 1-hr. rating; or 40 h.p. at 500 r.p.m. with a half-hour rating. The temperature rise on full load is 40 deg. cent. as an open machine, and 50 deg. cent. as an enclosed machine. The horse-power is proportional to the speed over a range

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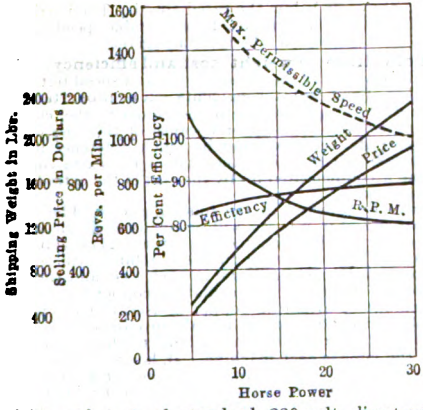


FIG. 66.—Weight and cost of standard 220-volt direct-current motors without base or pulley.

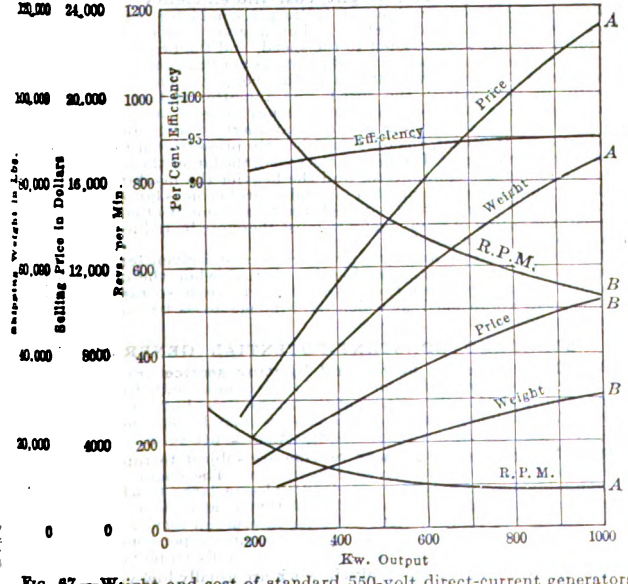


FIG. 67.—Weight and cost of standard 550-volt direct-current generators without base or bearings. *A*, slow-speed engine type; *B*, high-speed generators.

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of 30 per cent. above or below the rated speed. The maximum permissible speed is the highest that can be used for variable-speed operation with the particular line of machines on which data is given.

179. Effect of voltage on weight, cost and efficiency. If two machines are built on like frames for the same output and speed but for different voltages, the number of commutator segments will be proportional to the voltage and the commutator length will be proportional to the current. The low-voltage machine will be the heavier because of the long commutator, but, for moderate outputs, there will not be much difference in cost between a 120-volt and a 600-volt machine; the cost of the extra copper on the low-voltage machine is compensated for by the cost of the extra labor on the high-voltage commutator.

The losses will be affected in the following way: The windage, bearing friction, excitation and iron losses will be unchanged; the brush friction loss will be the smaller in the machine with the higher voltage; the contact resistance loss will be the smaller in the machine with the higher voltage because the contact drop is the same in each case and the loss is therefore proportional to the current. The armature copper loss will be unchanged if the same amount of armature copper is used in each machine, because, since the number of conductors is directly proportional to the voltage, the section of each conductor will be proportional to the current and the current density will be the same in each machine. If, however, due to the space taken by the insulation on the large number of conductors, the total amount of copper is the smaller in the machine with the higher voltage, then the copper loss will increase with the voltage and, for the same copper loss in each machine, the output of the high-voltage machine will be less than that of the low-voltage machine.

180. Effect of speed on weight, cost and efficiency. The output of a machine equals the product of (volts per conductor) × (current per conductor) × (number of conductors). For a given frame, the volts per conductor is directly proportional to the speed, and the product of (the current per conductor) × (number of conductors) is constant for a constant current density and a constant weight of armature copper. The output is therefore directly proportional to the speed. As a matter of fact the flux density must decrease as the speed and the frequency increase, in order to keep down the iron loss; but the current density may increase with speed due to better ventilation. However, the output is directly proportional to the speed, over a considerable range. The higher the speed, the larger the output, and therefore the longer the commutator and the heavier the machine.

At very low speeds the number of conductors becomes large and, on account of the amount of insulation required, the total amount of copper is less than normal; the rating of such machines must therefore be reduced in faster ratio than the speed is reduced.

The total armature loss for a given frame and a given temperature rise is equal to $k(A+B\times\text{r.p.m.})$ (see Fig. 52) so that while the output is directly proportional to the speed, the losses do not increase so rapidly; and, until turbo-speeds are reached, at which the windage losses become excessive, the efficiency increases with the speed.

STANDARD CONSTANT-POTENTIAL GENERATORS

181. Generators for power and lighting service are usually wound for 125 volts or 250 volts and are either flat-compounded or slightly over-compounded, so that the voltage at the lamps varies but little with change of load. The efficiency, weight, cost and speed may be obtained from Figs. 66 and 67. The regulation should be less than 2 per cent.

182. Generators for railway service are subject to rapidly fluctuating loads and to sudden and excessive overloads. The engine speed will drop considerably on an excessive overload unless a large flywheel is supplied. The machines are generally wound for 550 volts at no load and 600 volts at full load for city service, 1,200 volts for interurban service and 3,000 volts for trunk line electrification. In order to secure proper commutation under all load conditions, interpole machines are generally employed.

183. Generators for electrolytic work are usually low-voltage machines of large current capacity. When the terminal voltage is very low, the exciting current will be large if the machine is shunt wound, and the field rheostat

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will be relatively expensive; therefore such machines are often separately excited from a source of higher voltage. For electric smelting and other work where the machine is likely to be subjected to short circuits, shunt excitation is desirable, since a shunt generator will not maintain a large current through a short circuit (Par. 147). Because of the large currents to be collected, these machines have low-resistance brushes, a high current density in the brush contact and a wide brush arc. These conditions are bad for commutation, so that interpoles are often used. Since each armature circuit has comparatively few conductors in series, and these conductors are of large section, there will be large circulating currents unless equalizers (Par. 19) of large cross-section are used. Windings such as that shown in Fig. 14 are particularly suited for generators of this type. Electrolytic generators cost and weigh more than standard 550-volt machines, because of the large amount of commutator copper required. Accurate cost figures cannot be given since the design is generally special.

184. Boosters are used in constant-potential systems to compensate for feeder-drop or to aid in charging storage batteries, etc. Boosters carry large currents at low voltages and have long commutators in proportion to their output. In order that the flux may be proportional to the exciting current, the magnetic circuit must not be saturated; for this reason the machine is heavier than a machine of normal voltage and of the same output. Boosters often carry large currents in a weak magnetic field, so that they must be liberally designed for commutation. **Reversible boosters** often have laminated field systems. When reversing a machine with a solid field system, eddy currents set up in the solid masses by the change of flux prevent this change from being very rapid.

185. Exciters are generally flat-compounded for 120 volts or 240 volts if the excited machine is operated without an automatic regulator. When operated with an automatic regulator, the exciter must be capable of supplying a voltage about 40 per cent. more than normal. The magnetic circuit should not be highly saturated, in order that the necessary increase in excitation for a given increase in voltage of the excited machine may not be too large. Machines with solid poles are quite satisfactory, as very rapid changes of voltage are not desirable. The weight, cost and efficiency of such machines may be obtained from Fig. 66.

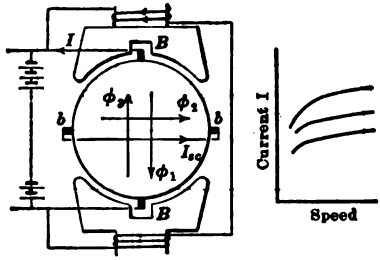


FIG. 68.—Rosenberg car lighting generator.

186. Variable-speed generators* used for the lighting of vehicles are required to give constant voltage over a wide range of speed. Many patents have been taken out on machines for this purpose. In one type the armature is moved axially out of the field by a governor, as the speed increases. In another type the brushes are shifted automatically as the speed changes. Other machines are driven by slipping belts or slipping clutches.

187. The Rosenberg variable-speed generator† is self-regulating and is shown diagrammatically in Fig. 68. The battery voltage is approximately constant and the shunt field sends across the air-gaps a flux ϕ_1, which is approximately constant. The armature cuts this flux and an e.m.f. is generated between brushes *bb*, but none between brushes *BB*. The former brushes are short-circuited, so that a current flows in the armature and sets up an armature field ϕ_2. Since the armature cuts this latter field, there is an e.m.f.

*Morgan. "Dynamos for Motor Road Vehicles," *Journal* of Inst. of Elec. Eng., Vol. XLVIII, p. 749.

†Hall. "The Rosenberg Generator," *General Electric Review*, Vol. XIII, p. 37.

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between brushes BB and a current I in the external circuit. This current I sets up a flux ϕ_2, which opposes ϕ_1, but can never exceed ϕ_1, so that I cannot exceed that value at which the armature ampere-turns per pole equal the shunt-field ampere-turns per pole. The relationship between current and speed for different shunt excitations is given in Fig. 68. The direction of the current I is independent of the direction of rotation of the machine.

188. Third-brush generators.* This type of machine is shown diagrammatically in Fig. 69. At no load the exciter voltage ab is half the terminal voltage ac, but armature reaction weakens the leading pole tip so that as the armature current increases, the exciter voltage ab decreases and thereby limits the current.

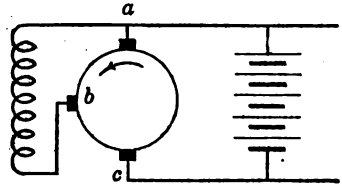


FIG. 69.—Third brush generator.

Another type of third brush generator† gives constant voltage over a wide range in speed and without the use of a battery. The machine has a 2-pole armature and a 4-pole field system excited so as to give two magnetic fields at right angles.

189. A system of car lighting by a shunt generator driven from the car axle is shown diagrammatically in Fig. 70. The diagram shows the conditions at standstill; the switch S is open, the generator is cut out and the battery supplies the lamps. As the car speeds up, the generator voltage increases and, when the value is reached for which solenoid F was set, the pull of the magnet closes the switch and connects the generator in parallel with the battery. The generator then delivers current to the battery and to the lamps, which current, flowing through coil H, helps to keep the switch closed. As the speed increases, the voltage of the generator and the battery current both increase, but when full-load battery current is reached, the pull of coil D acts to lessen the pressure on the carbon pile B and the generator voltage decreases; coil D therefore limits the battery charging current. When the battery reaches full charge, its voltage rises to the maximum value and then the pull of coil E acts to lessen the pressure on the carbon pile, preventing further rise of voltage and permitting the generator to supply only the current for the lamps. When the speed drops below a certain value, the battery voltage is higher than that of the generator; current then flows back through the coil H, thus releasing the switch S and disconnecting the generator from the circuit.

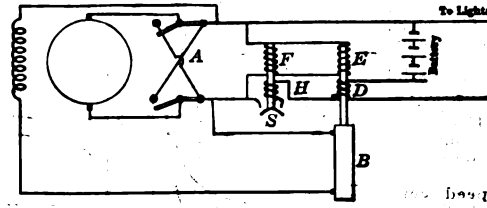


FIG. 70.—Car-lighting system.

Since the generator current should always be in the same direction no matter what the direction of motion of the car, a pole changer A is supplied; this consists of a double-throw switch operated by means of a mechanism on the shaft, which mechanism reverses the switch when the rotation of the generator reverses.

THREE-WIRE CONSTANT-POTENTIAL GENERATORS

190. The early three-wire systems were operated with two similar generator units connected in series and the neutral connected to the centre

* Langsdorf. "Principles of Direct Current Machinery," 2d ed., p. 434.
† S. R. Bergman. "D. C. Generator for Constant Potential at Variable Speed," *Proc.* A. I. E. E., Vol. XXXVII (Aug., 1918), pp. 1011–1018.

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point as shown in Fig. 71. In this system the voltages E_a and E_b can be regulated independently of one another.

191. **The earliest type of three-wire generator** was a machine which had two armature windings on the same core, revolving in the same magnetic field, with a separate commutator for each winding. This machine was connected as shown in Fig. 72. Since the armature reaction affects each

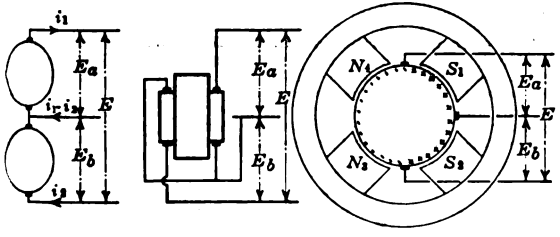


FIG. 71. FIG. 72. FIG. 73.

FIGS. 71, 72 AND 73.—Three-wire systems.

winding equally, it has no effect on the division of voltage, so that E_a differs from E_b only by the armature resistance drops in the two windings. These voltages cannot be regulated independently of one another by means of field rheostats.

192. **The Dettmar and Rothert machine** is of the **split-pole type** and is shown diagrammatically in Fig. 73 for the case of a two-pole armature revolving in a field system with four pole-pieces. Even on balanced load, the armature reaction strengthens the upper S pole and weakens the lower S pole, so that E_a increases and E_b decreases with increase of balanced load. To neutralise this effect, the weakened poles are compounded cumulatively and the strengthened poles are differentially compounded. If the shunt

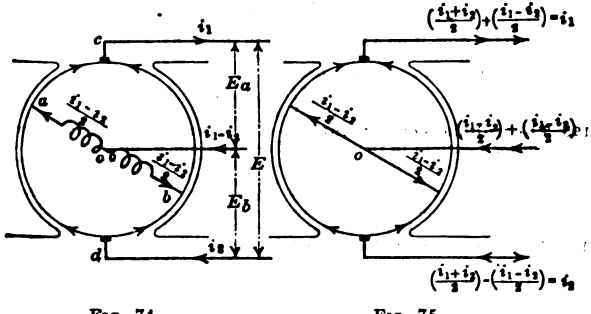


FIG. 74. FIG. 75.

FIGS. 74 AND 75.—Unbalanced currents in three-wire generators.

ls 2 and 4 are connected across E_a, and the coils 1 and 3 across E_b, the lancing will be better than if all four coils were connected in series across The voltages E_a and E_b can be regulated independently, by hand, when excitation is thus divided.

193. **The Dobrowolsky machine** is that generally used for three-wire eration. It is shown diagrammatically in Fig. 74 and consists of a stand- two-wire machine with a coil of high reactance and low resistance con-

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nected permanently across diametrically opposite points on the armature. The voltage between a and b is alternating and, even at no load, or when the load is perfectly balanced, an alternating current flows in this reactance coil. This current, however, is extremely small because the reactance is large. The center o of the coil is always midway in potential between the brushes c and d, and is connected to the neutral of the system. When the loads on the two sides of the system differ, the difference between the currents in the outside lines flows in the neutral wire and through the reactance coil, which offers only a small resistance to direct current.

194. The current distribution in the Dobrowolsky machine* may be considered as that due to the average current $(i_1+i_2)/2$ and a superimposed unbalanced current $(i_1-i_2)/2$, as shown in Fig. 75. The former of these currents flows in the outside lines, but does not pass through the neutral line, and so does not affect the potential of the point o. The unbalanced current is that which affects the voltages on the two sides of the system and this current is shown separately in Fig. 76.

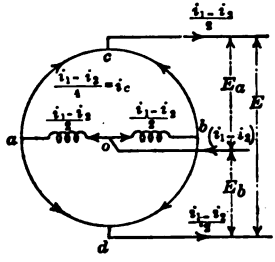


FIG. 76.

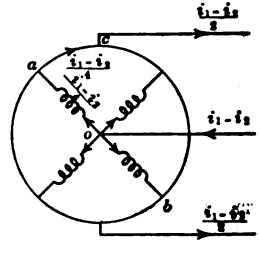


FIG. 77.

FIGS. 76 AND 77.—Unbalanced currents in three-wire generators.

If R_a is the resistance of the armature from brush to brush, then the resistance from a to c varies from 0 to $2R_a$ and, in the position shown in Fig. 76 it is equal to R_a. If R_b is the resistance of each of the two legs of the balance coil, the voltage drop from o to a is equal to $(i_1-i_2)R_b/2$; the drop from a to c equals i_cR_c and is alternating, with an average value of $(i_1-i_2)R_a/6$. The average drop from o to c is expressed by

$$\frac{(i_1-i_2)}{2}\left(\frac{R_a}{3}+R_b\right) \qquad \text{(volts)} \qquad (38$$

195. The unbalanced current (i_1-i_2) is generally limited to 25 per cent of the full-load current in the outside lines and, since the armature drop at full load equals the product of full-load current and R_a, and seldom exceeds 3 per cent. of E, it follows that the average voltage from a to c seldom exceeds 0.25 per cent. of E_a for 25 per cent. unbalanced current. Therefore the regulation of each side of the system is determined principally by the drop in the balance coil and can readily be kept within 2 per cent.

196. The use of two balance coils connected as shown in Fig. 77 results in a slight improvement in the machine. The average voltage drop from o to c in this case is

$$\frac{(i_1-i_2)}{4}\left(\frac{R_a}{3}+R_b\right) \text{ approx.} \qquad \text{(volts)} \qquad (39$$

and is apparently less than it would be with only one coil. But when two coils are used, as in Fig. 77, each one carries half of the current carried by the single coil in Fig. 76; therefore the wire used has half the section and each of the coils in Fig. 77 has twice the resistance of the coil in Fig. 76, and the drop from o to a is the same in each case. The drop from a to c is less in Fig. 77 than in Fig. 76, but the difference is so small that it has little effect on

* Hawkins. *Journal* of Inst. of Elec. Eng., Vol. XLV, p. 704.
Ferguson. "Characteristics of the Three-wire Generator," *Electrical World*, Vol. 64, pp. 1199–1204, Dec. 19, 1914.

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the regulation; it does, however, reduce the heating, because the unbalanced current has the shorter distance to travel in the armature when two balance coils are used, so that for the same armature temperature rise, the machine with the single balance coil requires slightly larger copper for the armature conductors than that with two balance coils.

197. **The rating of the balance coil.** The voltage between a and b (Fig. 74 to Fig. 76) is alternating and has a maximum value equal to E and an effective value equal to $E/\sqrt{2}$. The current in each half of the balance coil equals $(i_1-i_2)/2$, neglecting the small exciting current, so that the volt-ampere capacity of the balance coil equals $E(i_1-i_2)/2\sqrt{2}$. The normal output of the generator on balanced load equals EI volt-amperes, so that for 25 per cent. unbalanced current, the transformer rating in volt-amperes is only 9 per cent. of that of the generator.

198. **Compound-wound three-wire generators** have all the series coils on the N poles placed on one side of the circuit and all the series coils on the S poles placed on the other side of the circuit, so that the compounding is independent of the unbalancing of the load. The compounding has no effect on the voltage unbalancing.

199. **Parallel operation*** (Par. 229) is possible if two equalisers are used, one for each set of series field coils. The diagram of connections is shown in Fig. 78; six leads per machine are required because the circuit-breakers on the switchboard must be in the armature circuit and not in the equaliser circuit.

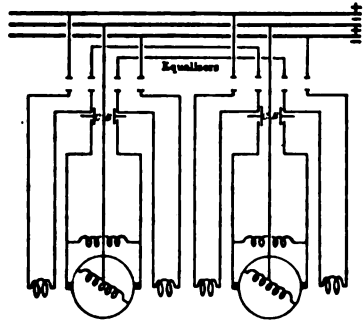


FIG. 78.—Parallel connection of three-wire generators.

STANDARD CONSTANT-POTENTIAL MOTORS

200. **Motors for general industrial service** should be of the open type whenever possible. The totally enclosed type should not be used unless absolutely necessary. For **crane service**, a totally enclosed series motor is used with a half-hour rating. For **elevator service**, an open compound motor is used, and for **freight hoists**, an open series motor each with a 1-hr. rating.

201. **Motors for railway service** are generally wound for 550 volts. They are series wound, and so constructed that they may be easily opened for repair. The steel frame is of the split-box type, so arranged that the complete armature may be easily removed. The armature core and commutator shell are mounted on a cast-steel spider, in order that a damaged shaft may readily be removed. Railway motors have undercut mica (commutator insulation) and abrasive brushes, but the tendency is to use interpoles in order to minimise sparking and flashing-over and to allow high speeds to be obtained for suburban service by field weakening. Since the load fluctuates between wide limits, interpole shunts should not be supplied (Par. 178).

Railway motors may be built for 1,200 volts, but the weight, size, and cost are increased for a given rating. A 100-h.p. 600-volt motor can be rebuilt to develop 75 h.p. at 1,200 volts; the larger the output the less will be the difference in rating between the high-voltage and the low-voltage machine. The 1,200-volt machine has the shorter commutator and therefore the longer core and the larger flux per pole, but has less copper in the slots due to the extra insulation required for the large number of conductors and the high voltage. A four-pole machine with an average of 20 volts between segments

* Bulletin on "I. T. E. Circuit Breakers."

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will have 240 segments and, with a minimum segment and mica of 0.2 in. (0.5 cm.) thickness will have a commutator diameter of about 15 in. (38 cm.). For further information see Sec. 16.

202. Mill motors for rolling-mill work are built like street railway motors set on feet, and are constructed in a similar manner in order that they may be readily repaired. The shafts are made stiffer than usual, which results in greater bearing friction and smaller efficiency than in standard motors. These motors weigh and cost about 20 per cent. more than standard motors of the same rating.

203. Mine motors are designed to operate in a damp atmosphere and must therefore be specially impregnated with waterproof compound.

204. Flame-proof motors,* for operation in explosive atmospheres, must have the current-carrying parts completely enclosed in flame-tight enclosures of non-inflammable material of sufficient strength so as not to be endangered by an explosion in the motor interior. The housings of such motors should never be opened in service except when the motor is completely disconnected from the supply circuit.

It is impossible to construct motors which are **gas-tight.** When the machine becomes heated, any gas which is in the case expands and some of it is forced out along the shaft. When the motor cools again, a fresh supply of gas will be drawn into the case. **Flame-tight** motors, wherein the transmission of an inside explosion to the outside is prevented, have proved feasible. There are two types: (a) Totally enclosed machines, constructed to withstand a pressure of 110 lb. per sq. in. (7.7 kg. per sq. cm.), are built in capacities up to about 25 h.p., but become large and expensive for greater outputs. (b) **Plate-protected motors** have openings which are filled with plates about 0.02 in. (0.5 mm.) apart so as to form a labyrinth passage for the gases; the function of this labyrinth is to cool the products of combustion.

205. Adjustable-speed motors are efficient only when operated by field control (Par. 164). For a wide range in speed, interpoles are required (Par. 165). The size and cost of the machine depend on the minimum speed at which it is necessary to supply the rated output, and the maximum speed is that at which the peripheral velocity reaches a safe limit. By the use of interpoles, deep slots may be employed, and the output for a given weight increased 10 per cent. over that for a non-interpole machine, but the cost per horse power is not reduced. The following table gives a list of ratings that may be obtained from a given frame, suitable windings being supplied; a speed range of 3 to 1 is ample for most purposes:

46 h.p. at 800 to 1,200 rev. per min.
40 h.p. at 700 to 1,200 rev. per min.
34 h.p. at 600 to 1,200 rev. per min.
29 h.p. at 500 to 1,200 rev. per min.
20 h.p. at 350 to 1,050 rev. per min.
17 h.p. at 300 to 900 rev. per min.
14 h.p. at 250 to 750 rev. per min.
11 h.p. at 200 to 600 rev. per min.

STANDARD CONSTANT-CURRENT GENERATORS

206. Open-circuit windings. Fig. 79 shows an armature with two open coils and four commutator segments. The voltage between A and B varies as shown in Fig. 80; the current is pulsating and only half of the armature is in use at any given instant.

207. In the Brush arc machine the commutator segments are made to overlap as shown diagrammatically in Fig. 81 and the brushes are wide enough to cover two overlapping segments. During the first one-eighth rev., coil C alone is active and the e.m.f. in that coil passes through its maximum value. During the next one-eighth rev., coils C and D are in parallel; the e.m.f. in C is decreasing and that in D is increasing. During the next one-eighth rev., coil C is cut out and coil D alone is active. When two coils are in parallel the higher e.m.f. in one coil tends to reverse the current in the coil of lower

* Baum. "Fire Damp-proof Apparatus," *General Electric Review*, Vol. XIII, p. 402.

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e.m.f. and, when the latter current is zero, the contact between the corresponding coil and the brush may be broken without sparking. Thus by rocking the brushes, a position of minimum sparking may be found.

208. Ratings of Brush arc generators. A 6,250-volt, 9.6-amp., 500-rev. per min. Brush machine weighs 9,590 lb. (4,350 kg.), occupies a floor space of 84 in. by 56 in. (2.1 by 1.4 m.) and requires 91 h.p. to drive it.

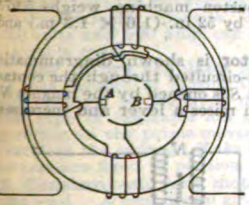


FIG. 79.—Open coil armature.



FIG. 80.—Voltage between *A B*.

209. The Brush regulator in its simplest form is shown in Fig. 63. A more recent type consists of two electromagnets rotated in opposite directions on a common axis by means of belts from the main shaft; between the magnets is a piece of iron which, when clutched by either electromagnet, causes the contact arm to move over the face of a rheostat which shunts the field windings. The excitation of the clutch magnets is controlled by a solenoid in the line circuit, so adjusted as to close the circuit of one magnet, or the other, according as the value of the line current is too great or too small.

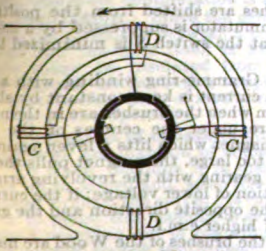


FIG. 81.—Brush type.

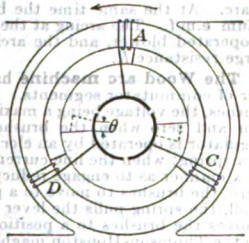


FIG. 82.—Thomson-Houston type.

Arc light generators.

210. The Thomson-Houston machine has three open coils spaced 120 electrical degrees apart, joined together at their inner ends, and connected to a three-part commutator at the outer ends, as shown diagrammatically in Fig. 82. At the position shown in Fig. 82, the e.m.f. in coil *C* is increasing, that in *D* is decreasing, and that in *A* is zero; coil *A* is therefore out of circuit at the instant. As the armature revolves, the e.m.f. in *A* increases and that in *D* decreases, until finally the brush disconnects the coil *D* and connects it in series with *C*. This cannot be done suddenly, however, or bad sparking would result; therefore the extra set of brushes (shown by dotted lines) is added and coils *A* and *D* are connected in parallel until the increasing voltage of *A* is able to reduce the current in *D* to zero, and thereupon the latter coil can be disconnected from the brush. The voltage regulation in this machine

* For tables of ratings of arc-lighting generators see Houston and Kennelly, "Recent types of Dynamo-electric Machinery," pub. 1898.

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is obtained by shifting the brushes. When the brushes are in the positio shown in Fig. 82, large e.m.fs. are being generated in the coils connected i series; when the brushes are shifted through 90 deg. these coils are generatin low e.m.fs. and the terminal voltage is a minimum. The mechanism whic shifts the brushes also varies the angle θ between brushes so as to secur good commutation with all brush positions.*

211. Rating of Thomson-Houston arc machines.* A 2,500-volt 10-amp., 829 rev. per min. Thomson-Houston machine weighs 5,975 lb (2,700 kg.), occupies a floor space of 64 in. by 52 in. (1.6 × 1.3 m.) and re quires 38 h.p. to drive it.

212. The Thomson-Houston regulator is shown diagrammatically in Fig. 83. The electromagnet *M* is short-circuited through the contact *S* When the line current is too strong, contact *S* is opened by the magnet *N* and the main current passes through *M*, which raises a lever and increases the

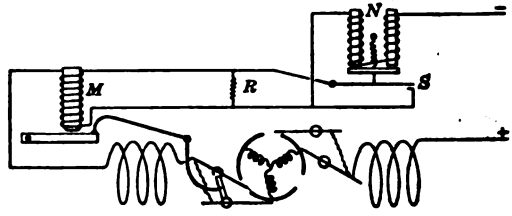


FIG. 83.—Thomson-Houston regulator.

brush arc. At the same time the brushes are shifted from the position o maximum e.m.f. The arcing at the commutator is suppressed by a mechan ically-operated blower, and the arcing at the switch *S* is minimised by th discharge resistance *R*.

213. The Wood arc machine has a Gramme-ring winding with a larg number of commutator segments. The current is kept constant by shiftin the brushes, the voltage being a maximum when the brushes are in the neutra position and zero when the brushes are under the centres of the pole The regulator is operated by an electromagnet which lifts a lever against th pull of a spring; when the line current is too large, the magnet pulls the leve in such a manner as to engage reduction gearing with the revolving armatur and cause the brushes to move to a position of lower voltage; if the current too small, the spring pulls the lever in the opposite direction and the gearin then moves the brushes to a position of higher e.m.f.

As in the Thomson-Houston machine, the brushes of the Wood arc machin are split into two parts separated by an angle θ (Fig. 82). As the brushe move under the poles, for the purpose of reducing the terminal voltage, th e.m.f. generated in the short-circuited coils increases, and must be counte balanced by a higher reactance voltage; this is readily obtained in a Gramm winding by reducing the brush arc so as to decrease the time of commutatio For sparkless operation, the brush angle θ should decrease as the brushes mov under the poles; this is accomplished automatically by the brush-rockin device.

214. Rating of Wood arc machines.* A 6,250-volt, 9.6-amp., 500 re per min. Wood arc machine weighs 14,600 lb. (6,600 kg.), occupies a flo space of 82 in. by 80 in. (2.1 m. by 2 m.) and requires 90 h.p. to drive it.

215. Constant-current generators for series arc lighting are near obsolete, although the Rosenberg machine (Par. 187), is coming into use f the operation of searchlight arcs. Direct-current series lighting systems a now in use, but in most cases are supplied from rectifiers (Sec. 6).

* Houston and Kennelly, "Recent Types of Dynamo-electric Machinery 1898.

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THURY SYSTEM

216. The constant-current system employing the types of generator described above is now rarely used, but the system has other applications, particularly in the transmission of energy over long distances (Sec. 11). Constant-current machines for operation on the **Thury System*** have been built for 5,000 volts and 150 amp. These machines have a two-circuit drum winding; a commutator with a large number of segments, so as to keep down the average potential between bars to about 20 volts; and two sets of brushes placed diametrically opposite. The claim has been made that units rated at 5,000 volts and 500 amp. can be constructed for sparkless operation, and at reasonable cost.

217. The Thury regulator is much like the Brush regulator (Par. 209), except that instead of moving the contact arm of a rheostat, it shifts the brushes through 90 electrical deg. as in the Wood machine (Par. 213). Another type of regulator has a relay in the main circuit which operates the governor on the prime mover in such a manner as to increase the speed, and therefore the voltage, if the line current becomes too small; the brushes in this case are fixed in position.

218. Constant-current motors must consume an e.m.f. which varies with the load. A centrifugal governor on the motor shaft causes the brushes to be shifted away from the neutral position when the speed rises due to a reduction in load, so that the counter e.m.f. is decreased, and also the total consumed e.m.f. The generator brushes are moved automatically at the same time to give this lower voltage.

219. Sparkless operation in all brush positions is made possible by so designing the machine that the number of armature amp.-turns per pole is equal to the exciting amp.-turns per pole. When the voltage between brushes is a maximum, the brushes are in the neutral position; but when this voltage is small, the demagnetizing effect of the armature is large, and, although the brushes are under the poles, the magnetic field is small. The poles are shaped so that the short-circuited coils are always in a suitable field and therefore commutation is as good as in an interpole generator.

220. Insulation. Since the generators and the motors are all connected in series, the potential between a machine and the ground may be very high, although the machine itself is wound only for 5,000 volts. Hence each machine must be insulated from the ground, and driven through an insulating coupling. The power-house floor is also made of insulating material for the protection of the operators.

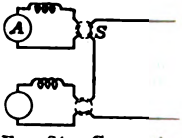


FIG. 84.—Connection of series generators.

221. Operation of constant-current machines. Fig. 84 shows the diagram of connections of the system. To place machine *A* in operation, it is first brought up to speed and, when full-load current flows in the local circuit, the switch *S* is thrown to the proper position to place the machine in series with the line. To take a machine out of operation, the brushes are brought slowly to the zero voltage position; then the switch *S* is manipulated to short-circuit the machine and disconnect it from the line.

To start up a motor, first see that the brushes are in the position of zero voltage, then switch the machine in series with the line and move the brushes slowly into the neutral position to bring the motor up to speed, after which the automatic regulator will keep the speed constant.

MOTOR-GENERATOR SETS

222. Direct-current sets are generally used to obtain energy for special purposes from a standard lighting and power system. Thus the generator of the set will often be a special machine.

223. The speed of these machines is seldom fixed by external considerations and may be chosen high in order to keep down the cost. The present tendency is to use speeds such as those given in Fig. 67 for high-speed generators; machines of higher speed will be cheaper and will operate satisfactorily but will rarely be accepted by operating engineers.

* Highfield, *Journal* of Inst. of Elec. Eng., Vol. XXXVIII, p. 471; Vol. XLIX, p. 848; Still, *Electrical World*, Vol. LX, p. 1093, 1912.

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224. Standard balancer sets,* as used for three-wire operation, consist of two like units coupled together, each wound for half of the total voltage and connected in series as shown in Fig. 85. On balanced load, they both run "light" as motors; but with unbalanced load, the currents flow as shown in Fig. 85 and machine M acts as a motor and drives G as a generator. The current in M is greater than that in G by that amount required to supply the armature losses. The motor speed drops with increase of load, and the generator voltage drops due to the decrease in speed and in excitation, so that E_g is less than $\frac{1}{2}E$. By crossing the shunt coils, as in Fig. 86, the regulation is improved. The motor field decreases with decrease of E_g and the speed of the set increases with load; furthermore, the generator excitation being taken from E_m, increases with load, so that with this connection the voltages are more nearly equal under all conditions.

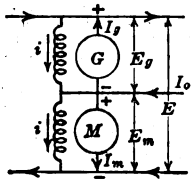


FIG. 85.

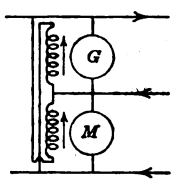


FIG. 86.

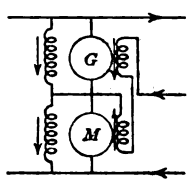


FIG. 87.

FIGS. 85, 86 AND 87.—Balancer sets.

225. Compound balancers are connected as in Fig. 87, so that the generator is always cumulatively compounded and the motor is compounded differentially, no matter in which direction the unbalanced current flows. This connection causes the balancer speed and the generator voltage to increase with the unbalanced load.

The generator current is expressed by the formula,

$$I_g = I_o \frac{\eta_m \times \eta_g}{1+\eta_m \eta_g} \quad (40)$$

and the motor current by

$$I_m = I_o \frac{1}{1+\eta_m \eta_g} \quad (41)$$

The efficiency in each case being given with the shunt-excitation loss neglected. The actual combined efficiency of the set is

$$\text{Eff.} = \frac{I_g}{I_m + 2i} \quad (42)$$

HOMOPOLAR MACHINES

226. Theory of Operation.† Faraday showed that, if the metal strip A, Fig. 88, be moved so as to cut lines of force, an e.m.f. will be established between the brushes a and b and a continuous current sent round the external circuit connecting them.

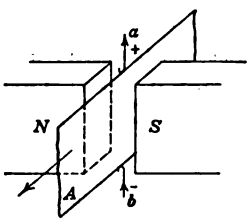


FIG. 88.—Faraday's demonstration.

227. The radial type, shown in Fig. 89, consists of a metallic disc, rotating between poles which are excited by field coils wound concentric with the shaft. The brushes are placed at a and b, and holes are cast in the yoke to allow access to the brushes. In Fig. 90, there are two discs mounted on the same shaft so that they are electrically connected

* Budd Frankenfield, *Electrical World*, Dec. 23, 1905; Lanier, *Electrical Journal*, Vol. IX, p. 1036.

† Gray. "Impossible Homopolar Machines," *Canadian Elec. News*, May 15, 1913.

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at the hub, and the total e.m.f. is twice that of one disc. Steel has been suggested for the disc material so as to reduce the reluctance of the magnetic circuit; this, however, would introduce a magnetic pull, due to inequalities in the air-gaps on the two sides of the disc, and this pull could be eliminated only by carefully adjusting the discs and then securing them in such a way as to prevent end play.

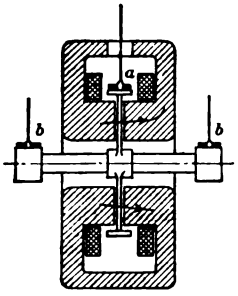


FIG. 89.

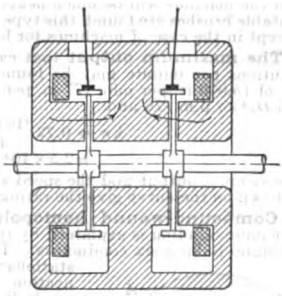


FIG. 90.

FIGS. 89 AND 90.—Radial type of homopolar machine.

228. The axial type, shown in Fig. 91, consists of a metallic cylinder rotating in a uniform magnetic field. The voltage of such a machine is low; a 300-kw., 500-volt, 3,000-rev. per min. machine with an armature diameter of 19.3 in. (49 cm.), effective core length of 12.2 in. (31 cm.) and a peripheral velocity of 15,200 ft. per min. (77 m. per sec.) generates 41.5 volts per conductor in a field of 112,000 lines per sq. in. (17,300 per sq. cm.) density. In this case twelve conductors in series are required for 500 volts, and each conductor requires two slip-rings, with brushes on each ring adequate to carry the full-load current, the rubbing velocity being about 15,000 ft. per min. (77 m.p.s.).*

229. The brush friction loss is very large and the total contact drop of twenty-four contacts in series is also large. The efficiency is about 88 per cent. at half load and 91 per cent. at full load.

230. The output equation (Par. 59) for a homopolar machine is

$$D_a^2 L_c = \left(\frac{\text{watts}}{\text{r.p.m.}}\right)\left(\frac{60.8\times 10^7}{\mathfrak{B}_g\ q}\right)\text{(cu. in.)} \quad (43)$$

where $\mathfrak{B}_g$ in the above 300-kw. machine is 112,000 lines per sq. in. and is limited by saturation; q in the above machine equals $12\times 600/\pi\times 19.3 = 120$ ampere-conductors per in., a value which cannot be increased without increasing the number of brushes, and which cannot reach the value given in Fig. 29 unless some brush is devised which will collect about 1,200 amp. per sq. in. (186 amp. per sq. cm.) of contact surface.

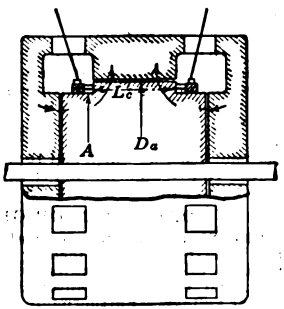


FIG. 91.—Axial type of homopolar machine.

Substituting the above values for $\mathfrak{B}_g$ and q the following equation is obtained.

$$D_a^2 L_c = 45\left(\frac{\text{watts}}{\text{r.p.m.}}\right) \quad \text{(cu. in.)} \quad (44)$$

* Noeggerath. *Trans.* A. I. E. E., Vol. XXIV, p. 1.

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Now the flux density in section *A*, Fig. 91, is limited to about 130,000 lines per sq. in. (20,000 per sq. cm.) so that $D_a = 1.7\,L_a$ approximately, and therefore $D_a^2 = 76$ watts/rev. per min., with the above limitations.

231. Weight and cost. * Because of the low value of ampere-conductors per in., made necessary by the brush rigging, the value of $D_a^2 L_a$ for a homopolar machine will generally be greater than for a machine of the standard type and the machine will be much heavier and more expensive. Therefore, until suitable brushes are found, this type of machine is not likely to be widely used except in the case of machines for low voltages and large currents.

232. The maximum output that can be obtained for a given number of revolutions per minute may be found by assuming a limiting peripheral velocity of 15,000 ft. per min. (77 m. per sec.). Then the output in watts is equal to $D_a^2 \times$ r.p.m./76 and

$$\text{kw} = 0.72\,\frac{(\text{perip. vel.})^2}{\text{r.p.m.}^2} \times \frac{1}{1000} \qquad (45)$$
$$= 2.5 \times 10^6/(\text{r.p.m.})^2$$

The maximum output and the speed are plotted in curve 4, Fig. 32. The points shown on the curve give the ratings of two machines now in operation.

233. Compound-wound homopolar machines. The idea underlying the compounding is explained by the diagram in Fig. 92, which relates to a machine having six conductors. The brushes *E* are connected to the stationary conductors *H* by means of connection pieces *G*. Only a portion of the whole length of *G* is actually employed to carry current, and the amount of this active portion can be varied by the brush rocker *F*. In practice it is sufficient to have a flexible lead instead of the fixed conductor *G*.

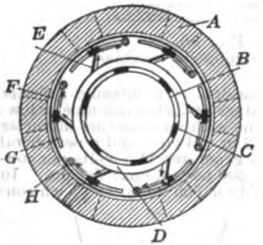


FIG. 92.—Compounding of homopolar machines. *B*, armature conductors; *C*, insulation between conductors; *D*, slip rings.

234. Homopolar machines may be made self-exciting and Noeggerath points out that homopolar machines may even be operated without the use of a field coil.

235. Standard lines of homopolar machines are not on the market; the machines are heavy and expensive if the ampere-conductors per in. are kept low so as to have a reasonably satisfactory brush rigging (Par. **230**), and are troublesome in operation unless they are excessively large. The troubles encountered in the construction and operation of a homopolar machine are described by Lamme† in connection with a 2,000-kw., 260-volt, 7,700-amp., 1,200-rev. per min. machine which had 16 slip-rings operating at a peripheral velocity of 13,200 ft. per min. (67 m. per sec.) and copper leaf brushes set against the direction of rotation, the rings being lubricated with graphite.

OPERATION OF GENERATORS AND MOTORS

236. Shunt-wound generators in parallel. *A* and *B*, Fig. 93, are two similar generators feeding the same bus bars *C* and *D*. If machine *A* tends to take more than its proper share of the total load, the voltage of *A* falls, and the load is automatically thrown on *B*, the machine with the higher voltage. Furthermore, if the engine connected to *B* fails for an instant, that machine slows down, its generated e.m.f. falls, and current flows back from the line to operate it as a motor. Since the excitation remains unchanged, the machine will run at normal speed and in the same direction as before, and, as soon as the engine recovers, will again take its share of the load.

237. Division of load between shunt generators in parallel. The external characteristics of the two machines are shown in Fig. 95. At

* Pohl. "The Development of Tubo-generators," *Journal* of Inst. of Elec. Eng., Vol. XL, p. 239.

† Lamme. *Trans.* of A. I. E. E., Vol. **XXXI**, p. 975.

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voltage E, the currents in the machines are I_a and I_b, and the line current is I_a+I_b. To make machine A take more of the load, its excitation must be increased, in order to raise its characteristic curve. If a 100-kw. machine and a 500-kw. machine have the same regulation, and therefore the same drop in voltage from no load to full load, then, as shown in Fig. 96, the machines will divide the load according to their respective capacities.

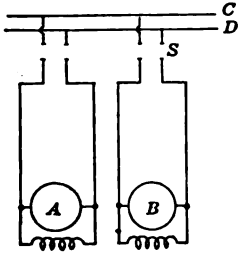


FIG. 93.—Shunt.

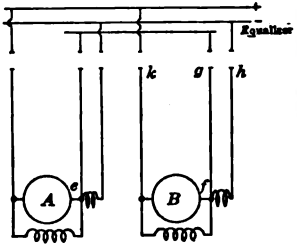


FIG. 94.—Compound.
Connections for parallel operation.

238. Compound-wound generators in parallel. A and B, Fig. 94, are two compound-wound machines. If machine A tends to take more than its proper share of the load the series excitation of A increases, its voltage rises and it takes still more of the load, so that the operation is unstable. Furthermore, if the engine on B fails for an instant, that machine slows down, its generated voltage falls and current flows back from the line to operate it as a motor. Under these conditions the shunt excitation remains unchanged, but the current in the series coils is reversed, so that, running as a motor in a weak field, the machine will tend to increase in speed and possibly run away.

239. Equalizer bus. To prevent instability when compound-wound machines are operated in parallel, a bus bar of large section and negligible resistance, called an equalizer bus, is connected from e to f as in Fig. 94. Points e and f are then practically at the same potential; therefore the current in each series coil is inversely proportional to the resistance of that coil, is independent of the armature current, and is always in the same direction. The machine ammeter, which indicates (at the switchboard) the current output, should always be connected in series with the lead k, Fig. 94. In **interpole machines**, the interpole winding is considered as part of the armature.

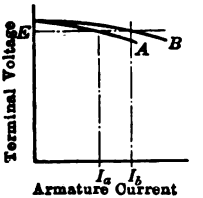


FIG. 95.

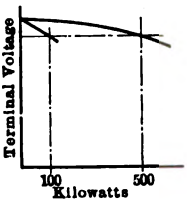


FIG. 96.

FIGS. 95 AND 96.—Division of load between two shunt generators in parallel.

240. Series shunt. When a single compound generator has too much compounding, a shunt in parallel with the series field coils will reduce the current in these coils and so reduce the compounding. When compound machines are operating in parallel, using an equalizer bus, the current in the series field coils depends only on the resistance of these coils; and a series shunt connected to one machine does not reduce the compounding of that machine alone, but also that of all the other machines with which it is operating in parallel. In order to reduce the compounding of a single machine, a resistance must be placed in *series*, and not in parallel with the series field

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coils. A combination of series and shunt resistances can also be employed. This adjustment is made after erection. If one machine is found to take more than its share of the load, then its compounding must be reduced by means of a resistance placed in series with its series field coils.

241. Starting and stopping a single shunt-wound generator. It is generally safest to start with the machine entirely disconnected from the external circuit and with the field rheostat all in circuit. Then bring the generator up to speed and cut out the field resistance until the voltage of the generator is normal. The main line switch may then be closed and further adjustment of voltage made if necessary.

To stop the machine, open the feeder switches, insert all the resistance in the field-coil circuit, then open the main switch and shut down the engine.

242. Starting and stopping shunt-wound generators in parallel. Assume that machine *A*, Fig. 93, is running; it is required to throw machine *B* in parallel with it. This latter machine must on no account be connected to the line while coming up to speed, otherwise it will form a short circuit across the machine which is already in operation. To place machine *B* in operation, bring it up to speed with the switch *S* open, adjust the shunt rheostat until $E_b = E_a$, then close switch *S* and increase the excitation of *B* until it takes its share of the load. To disconnect this machine, its excitation should be reduced until machine *A* carries the entire load; the switch *S* may then be opened. When shunt machines are being connected in parallel for the first time, the polarity of the switches should be carefully tested with a voltmeter or its equivalent.

243. Starting and stopping compound-wound generators. A single machine is started and stopped in the same way as a shunt machine (Par. **241**). To place machine *B*, Fig. 94, in parallel with machine *A*, which is already running, bring the machine up to speed and excite it to give normal voltage; first close switches *g* and *h* in order to excite the series coils, then make E_b equal to the bus-bar voltage and close switch *k*; the machine may then be made to take its share of the load by increasing the shunt excitation. To disconnect the machine, reduce its load to zero as in the shunt generator, and open the three switches in the reverse order.

Three separate switches are necessary for large machines, because of the large currents. For smaller machines, one double-pole switch for *g* and *h*, and a single-pole switch *k*, are sometimes used. For small machines, a three-pole switch is often used, but then the main switch is closed before the series field has its proper value and there is a momentary disturbance.

244. Starting and stopping motors. All except small motors, rated at a small fraction of a horse power, should be provided with a **starting box** or **starting rheostat.** Such starters, on constant-potential systems, consist in general of graded resistance connected in series with the armature, and eliminated step by step as the motor comes up to speed. The starting torque, as well as the running torque, is given by Eq. 36, Par. **159**; therefore in order to keep the starting current as small as possible, the magnetic flux should be as large as possible and the field coils should be fully energized before the armature receives any current. The counter e.m.f. at standstill is zero, and therefore the series starting resistance is necessary to limit the starting current to a safe value. Starters should be equipped with an **automatic release** which will operate under the conditions of no terminal voltage, or no current in the shunt field coils, so that the motor will not be burnt out when the terminal voltage is re-established or when the field circuit accidentally opens. For further information on starters see Sec. 5, and for information on motor control see Sec. 15.

Shunt motors may be stopped by merely opening the line switch; such motors should not be stopped by returning the handle of the starting box to the "off" position, because this method requires the opening of the field circuit while energized and gives rise to a momentary but very severe induced e.m.f. The handle of the starting-box should automatically return to the "off" position before the motor finally comes to a dead standstill.

245. Field discharge. If the field circuit be suddenly opened while carrying current, then, due to the rapid decrease of flux through the large

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number of field-coil turns, a large e.m.f. will be induced between the two open ends. This may be sufficient to break down the insulation between the field coils and the poles. To prevent this, when a motor is disconnected from a line, the field coils should be short-circuited through the armature winding at the instant the line circuit is opened, the necessary connections being made by the starter.

246. Installation of motors and generators. The machine should, if possible, be placed in a cool ventilated position which is free from dirt, dust, or moisture. Machines required to operate in damp places should have the coils specially treated. The foundation should be solid to prevent vibration. If the machine is belted, the belt tension should not be too great, the distance between belt centres too short, or the pulley too small; the pulley should not have a diameter less than that recommended by the manufacturer. The belt should be flexible and without lumpy joints and the bottom side should be the tight side. After erection, clean the bearings by pouring in gasoline, drain this off through the drain cocks and then fill the bearings with light mineral oil. Before starting, see that there are no loose parts and that the brushes are making firm contact.

247. Starting generators for the first time. Bring the generator slowly up to speed with the field circuit open and see that the oil rings operate properly; then close the shunt field switch and bring the voltage up to normal. Run the machine without load for an hour, after which the load may gradually be increased. Generators should be thoroughly dried out in every instance before they are placed in commission.

248. Starting motors for the first time. Check the connections to make sure that they are correct and secure. See that the controller handle is in the starting position, then close the line switch. If the motor does not start on the first or second notch of the controller, open the line switch and look for the trouble. When starting, bring the controller handle over slowly to the running position, allowing the motor to gather speed, but do not run on the starting notches for any length of time. Run the motor without the belt for half an hour (this cannot be done with a series motor) and then put on the load. When shutting down, open the line switch and see that the controller handle returns to the starting position before the motor finally stops.

249. Operating instructions. Keep oil away from the commutator, brushes and windings. Do not allow dirt or dust to accumulate in or around the machine. Do not lubricate the commutator with oil; a piece of muslin moistened with vaseline may be used to clean the commutator. Emery is a conductor and should not be used in fitting brushes or cleaning the commutator; use sandpaper and do not use it on the commutator too frequently. Do not use greater brush tension than necessary; tension greater than 2 lb. per sq. in. (0.14 kg. per sq. cm.) is seldom required. When replacing brushes, use the quality and size originally supplied with the machine, and fit them to the commutator with sandpaper before use; a strip of sandpaper should be placed on the commutator below the brushes, sand side up, and pulled through in the direction of motion of the commutator. Do not open generator-field circuits quickly (Par. 113); open the switch slowly, permitting the arc to extinguish gradually, which should take about 5 sec. On large generators use a field discharge resistance, which is connected across the terminals as soon as the field switch opens; see Fig. 97.

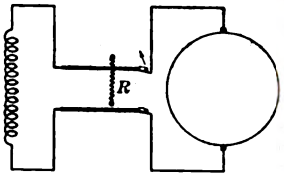


FIG. 97.—Field discharge resistance.

Do not stop quickly on account of a hot bearing, but slow down the machine and apply good clean oil. A quick shut-down will cause the bearing to "freeze." Inspect and clean the machine periodically.

250. Poor commutation is generally due to one or more of the following causes:

(a) Brushes not in the proper position.

(b) Bad spacing of the brush sets. This may be checked by counting the number of commutator segments between adjacent brush sets.

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(c) Projecting mica. This cause may be removed by cutting out the mica between segments for $\frac{1}{16}$ in. (0.16 cm.) below the commutator surface.

(d) Rough commutator, generally caused by sudden rushes of current. When such current rushes are inherent under the operating conditions, and interpoles are not employed, it may be advisable to use abrasive brushes to keep the commutator free from rough spots.

(e) Flat bars, produced because some of the commutator segments are softer than others.

(f) High bars, generally due to soft spots in the mica clamping cones.

(g) Grooved commutator, may be prevented by staggering the brush sets so that the space between two brushes of one set is covered by a brush of the next set and the commutator wears down evenly.

(h) Poor brush contact, due to imperfect bedding of the brushes, to dirt, or to burning of the contact.

(i) Worn brushes being replaced by others of the wrong quality or size.

(j) Sticky brushes, which do not move freely in box holders and so do not follow irregularities of the commutator.

(k) Vibration due to want of balance in the armature, to poor foundations, or to a badly laced belt.

(l) Chattering of the brushes, which can generally be cured temporarily by cleaning the commutator with a piece of muslin moistened with vaseline, and may be cured permanently by changing the brush angle.

251. Armature winding troubles are generally due to the following causes:

(a) A broken coil, generally at the commutator end, caused by the wire connected to the commutator being too tight, excessive vibration, poor soldering at the commutator neck, or the use of copper which was not properly annealed. This trouble causes a bad arc at the instant the brush breaks contact with the segment connected to the broken coil. The trouble can be fixed temporarily by short-circuiting the commutator segments connected to the damaged coil, thereby cutting it out, care being taken not to short-circuit the coil itself.

(b) A short-circuited armature coil may be due to damaged insulation between turns or to an accumulation of copper dust in the commutator necks. A large local current will flow in this coil and cause it to become hot and to smoke.

(c) An armature coil may be reversed during repairs. The e.m.f. of the reversed coil opposes that of the other coils so that one circuit in the armature will generate less than normal voltage (Par. 19). At the moment of commutation, the conductors of this coil will be under the wrong pole tips and local sparking will take place.

252. Field-coil troubles are generally due to the following causes:

(a) An open circuit: If the motor is series wound, the machine will stop and cannot be started again; if a shunt motor, the machine will speed up as the flux decreases (Par. 163) and the line current will increase as the back e.m.f. diminishes, until the circuit-breakers open. If the machine is a shunt or compound generator, the generated e.m.f. will greatly decrease and a large current will flow into the machine from other generators which are operating in parallel with it, and open the circuit-breakers.

(b) A short circuit will reduce the field-coil resistance and in the case of a shunt machine, will cause the exciting current to increase and the temperature to rise. The m.m.f. of the damaged coil will be reduced and that of the other coils increased, so that the strengths of the poles will be different (Par. 19). The average flux per pole will be unchanged in a shunt machine, but will be reduced in a series machine.

(c) Reversed field coils will cause adjacent poles to have the same polarity. The polarity can be tested with a compass or, if that is not available, with a piece of soft iron which will lie along the lines of force and therefore bridge the poles if the polarity is correct, but will tend to lie axially in the direction of the shaft if the polarity is wrong.

253. The effect of wear in the bearings is to throw the armature out of centre with respect to the pole-pieces and cause an unbalanced pull (Par. 19).

254. End thrust causes heating of the bearings and is generally due to projection of the armature core beyond the magnetic field (Par. 95). End thrust may also be due to the fact that the shaft is not horizontal.

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255. Residual magnetism of the generator fields may be "killed" by a short circuit. When this happens, the field coils must be excited from an external source, using batteries if nothing else is available.

256. Humming may be cured by chamfering the pole tips.

TESTING

257. Purpose of testing. Commercial tests are made on standard machines to make sure that they have been properly constructed. **Acceptance tests** are made on important machines to make sure that they meet the guarantees. **Special tests** are made by the designer to find the limits of a new machine and to obtain constants and data to be used on future designs.

258. No-load saturation, friction and iron-loss tests. To make this test the machine is separately excited, connected as shown in Fig. 98, and driven as a generator at the rated speed by a shunt motor M of such size that the rated output of the motor is approximately equal to the largest loss to be measured. The losses in the driving motor should have been previously determined and should be known for all inputs. The generator is excited to

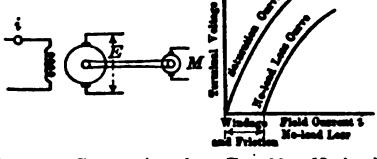


FIG. 98.—Connections for large machine.

FIG. 99.—No-load curves.

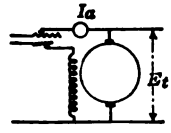


FIG. 100.—Connections for small machine.

No-load saturation, friction and iron-loss tests.

give about one and one-half times normal voltage; the excitation is then gradually reduced, the speed being kept constant, and simultaneous readings are taken of generator voltage, speed and exciting current, also of motor input, speed and excitation. The losses in the motor for a definite voltage, current, speed and excitation are known; the output can therefore be found and is equal to the sum of the iron, windage and friction losses in the generator, an allowance being made for the loss in the belt. The results are plotted as in Fig. 99. The loss with zero excitation is the windage and friction loss, from which the windage and bearing friction can be separated by taking a reading with the brushes lifted.

259. The brush loss varies greatly with the condition of the contact surface and a note should be made on the test sheet as to whether the test was made before or after the heat run and whether or not the commutator was cleaned and lubricated before the test was made.

260. The saturation and no-load loss test for a small motor is generally made by separately exciting the machine, connecting it as shown in Fig. 100, and running it idle at normal speed. The armature voltage is varied with a rheostat in the armature circuit and the excitation is adjusted to keep the speed constant. This excitation will be approximately the same as the no-load excitation as a generator, since, at no load, the applied voltage is practically equal to the back e.m.f. (Par. 157). The armature input will be the sum of the windage, friction and iron-losses and also the small copper-loss due to the no-load armature current; the latter loss can be calculated and deducted.

261. Armature resistance. This is generally measured by passing a known current through the stationary armature and measuring the voltage drop between the brushes and also across the terminals of the machine. This latter value is not the true voltage drop between the terminals, since the contact resistance when the machine is running is different from that when the machine is stationary.

The armature resistance is sometimes determined by passing a current through the armature and also through a standard resistance of approxi-

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mately the same value and at least the same current-carrying capacity, and comparing the drops of potential across each, in which case the current need not be measured.

262. **The field-coil resistance** is determined by passing a known current through the coils and measuring the drop of potential across the field terminals.

263. **Load tests** on machines of considerable size must be made by some method whereby the power developed by the machine is not dissipated, but is made available for the test; otherwise the power-house capacity may not be large enough to test many machines and the cost of the test will be excessive.

264. **Blondel's loading-back method.** Two identical machines are required for this test. They are separately excited, connected together mechanically to run at the same speed, and their armatures are connected electrically in opposition as in Fig. 101 so that, when equally excited, there is no current in the armature circuit. An auxiliary motor M is belted to the set

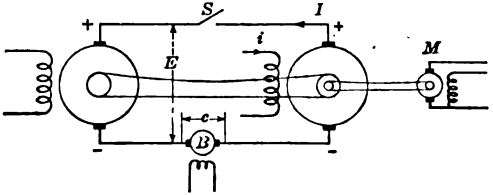


FIG. 101.—Blondel method.

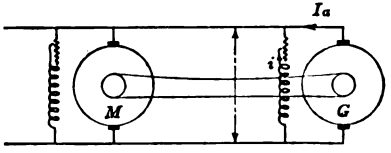


FIG. 102.—Kapp method.
Loading back tests.

and should have a capacity large enough to supply the no-load losses of both machines. The booster B must carry full-load current and is used to circulate the current through the armatures of both machines. The set is brought up to speed by the auxiliary motor, the switch S being open. The fields are then excited until the voltage E is normal and the voltage across the switch S is zero. This switch may then be closed and, by suitably exciting the booster, any desired armature current may be made to circulate. The booster supplies the copper-loss and the motor M supplies the other armature losses of both machines so that EI is the generator output; one-half the output of M is equal to the sum of the windage, friction and iron-losses of one machine; one-half of eI is the copper-loss of one machine; and Ei equals the excitation loss of one machine, from all of which the efficiency may be found.

265. **The regulation** of a generator, or of a motor, may be determined from Blondel's test. The machines in this case need not be identical, but they must be of the same voltage, and the output of the testing machine must not be less than that of the machine to be tested. In the test for generator regulation, start with normal voltage E and no circulating current; then excite the booster to give the desired current I_a and measure E_t, the terminal voltage. Plot E_t and I_a as in Fig. 58. In the test for motor-speed regulation, keep the voltage across the motor terminals constant

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by means of the booster, and vary the speed of the auxiliary motor M until the circulating current has the value desired. Plot the speed and I_a as in Fig. 64.

266. Hopkinson's test. This test is similar to Blondel's, but the booster is eliminated and the auxiliary motor is used to supply all the losses, the current in the armatures being circulated by weakening the field of one machine and strengthening that of the other. The iron-losses in the two machines are different because the fields have different excitations, so that, while the method is satisfactory for regulation and heating, it is not satisfactory for efficiency.

267. Kapp's method is preferred to Hopkinson's and is the one generally adopted in commercial work for regulation and heating tests; the efficiency of a machine is generally calculated from the losses. The diagram of connections is shown in Fig. 102. The losses are supplied from the testing circuit and are easily measured, but, since the copper-losses in the two machines are different, as also are the iron-losses, the method should not be used for an accurate determination of efficiency.

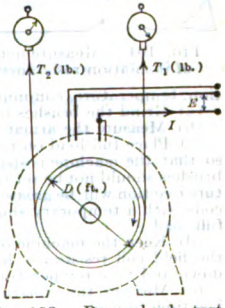


FIG. 103.—Prony-brake test.

268. Load tests on series motors. When a large number of **railway motors** have to be tested the loading-back method of test is used. Two motors are connected together as shown in Fig. 101 and are geared to the same countershaft so as to run at the same speed. This countershaft, driven by an auxiliary motor supplies the mechanical losses. The field coils are connected in the armature circuit and a booster is also placed in this circuit to supply the copper losses.*

269. Prony brake test. The efficiency is seldom determined by direct measurement of input and output except in the case of small motors which are connected directly to the line and the load then measured by means of a water-cooled **prony brake** as in Fig. 103.

$$\text{Eff.} = \frac{746\pi\, D\ (\text{r.p.m.})(T_1 - T_2)}{33{,}000\ EI} \qquad (46)$$

270. In constant-current arc generators, the load losses are generally large, and the efficiency of such machines is obtained by measuring the output electrically, and the input by means of a driving motor whose efficiency is known.

271. Load saturation test. The generator is driven by a motor of the same voltage and of larger output, and the machines are connected to the testing circuit as in Fig. 102. Starting at about 20 per cent. above normal voltage and with full-load circulating current, the excitations of the two machines are gradually reduced and a series of readings of E_l and i are taken, I_a being constant. The results are plotted as in curve 2, Fig. 19.

272. Heat run. The machine is connected as in Fig. 102 and operated at rated speed and voltage, with the desired circulating current. The suggestions contained in the A. I. E. E. standardization rules, Sec. 24, regarding measurement of temperature and conditions of test, should be followed.

273. Insulation resistance may be measured with a megger (Sec. 3) or by means of a high-resistance voltmeter connected as in Fig. 104. In the latter case the insulation resistance equals the resistance of the voltmeter multiplied by the ratio $(E-e)/e$, where E, the voltage of the testing circuit, should be the same as the normal voltage of the machine being

*For modifications of this test see:
Workman, R. E. "Factory Testing," *Electric Journal*, Vol. I, p. 551.
Fay, C. J. "Testing Large Motors," *Electric Journal*, Vol. III, p. 525.

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tested, and e is the voltmeter reading or the drop in voltage across the voltmeter resistance.

274. Puncture test. To test the insulation, a high voltage is applied between the armature winding and the frame, between the field windings and the frame, and also between the shunt and the series field coils with the shunt winding disconnected from the armature. The test voltage is obtained from a small testing transformer of adjustable ratio and should be raised to the desired value smoothly and without sudden large increments; the maximum should be applied for 1 min. unless otherwise specified, and then gradually decreased. The recommendations given in Sec. 24, should be followed.

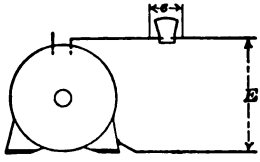


FIG. 104.—Measurement of insulation resistance.

275. Acceptance tests. A compound generator to be tested for efficiency, regulation, temperature, commutation and insulation would be handled as follows:

(a) Grind the brushes in place with sandpaper.

(b) Measure the armature and the field coil resistances.

(c) Place full load on the machine (Par. **272**). Adjust the brush position so that the machine is sparkless over the desired range of operation. The brushes should not be set further forward than necessary, otherwise the armature reaction will be greater than it need be. Adjust the current in the series coils with a temporary shunt to give the required voltage at no load and at full load.

(d) Keep the machine on full load until the temperatures, as indicated by the field coil resistance, have become approximately stationary; then shut down and take temperatures.

(e) Measure the armature and the field coil resistances before the machine has time to cool.

(f) Give the machine an overload run, if that is desired.

(g) Make the regulation test (Par. **265** and **267**); then since the machine is properly connected, a full-load saturation test may be made for the information of the designer, if required.

(h) The no-load loss may be determined by running the machine idle as a motor (Par. **260**), but the designer will probably want information in regard to the separate losses (Par. **258**). The test results are then worked up, and, if the machine is satisfactory, the insulation resistance is measured and the puncture test made.

276. Commercial or shop tests. For standard machines on which the designer has all the information he requires, such a complete test (Par. **275**) is not necessary. The machine should be run idle at normal speed and voltage to make sure that the no-load losses are not too high due to poor material or poor construction, and that the excitation is not too large or too small. The armature and field coil resistances are checked with the calculated values. The machine is run for an hour at 25 per cent. overload to test the mechanical construction and then run idle at 50 per cent. above normal voltage to test the insulation between turns. The speed may be increased during this latter test. The insulation resistance is then measured and the puncture test made. For further information see the series of articles on shop testing by R. E. Workman in Vol. I of *Electric Club Journal*.

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SECTION 9

CONVERTERS AND DOUBLE-CURRENT GENERATORS

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SECTION 9

CONVERTERS AND DOUBLE-CURRENT GENERATORS

SYNCHRONOUS CONVERTERS

BY F. D. NEWBURY, M.E.

GENERAL THEORY

1. Comparison with separate synchronous motor and direct-current generator. The theory of the synchronous converter is best explained by the similarity of the converter to a synchronous motor driving a direct-current generator. The converter combines the characteristics of both motor and generator in the single armature winding. This winding is provided on one end with a commutator as in a direct-current generator, and on the other with collector-rings and taps to the winding as in a revolving-armature synchronous motor. Alternating current is supplied through the collector-rings, and with no direct-current load the synchronous converter operates purely as a synchronous motor. Its speed is determined by the frequency and number of poles and the flux is fixed by the impressed voltage, just as in a synchronous motor.

2. Excitation. In the synchronous converter, as in the synchronous motor, the magnetic flux and the corresponding net exciting ampere-turns are determined solely by the impressed voltage. If it is attempted to vary the exciting ampere-turns and flux by variation of the main field excitation, the latter variation is neutralized by an equivalent change in excitation brought about by a change in phase and value of the armature current, so that the flux and net excitation remain constant. Increased excitation in the main field winding produces a leading current in the armature (leading with respect to the line voltage) which, in the majority of transmission lines serving synchronous converters, is beneficial to line power-factor and voltage. Conversely, under-excitation produces a lagging current which is detrimental to the power-factor and voltage of such lines.

3. Ratio of alternating voltage to direct-current voltage. Assuming the synchronous converter to be operating without direct-current load, it will be clear that the direct-current voltage between brush arms will, through the action of the commutator, have a value equal to the maximum instantaneous value of the alternating voltage, giving proper consideration to the relative points in the armature winding to which, at any instant, the brushes and collector-rings are connected. In the single-phase, two-phase, and six-phase diametrically connected converters, the direct-current brushes and collector-rings are connected to equivalent points on the armature winding, so that the ratio between the alternating and direct-current voltages is simply the ratio between the effective and the maximum alternating voltages. In the three-phase converter, the collector-rings are connected to points 120 electrical degrees apart, while the direct-current brushes are connected to points 180 electrical degrees apart, so that the voltage ratio is affected by this difference. The theoretical ratios are shown in Par. 4. See Par. 36 and Figs. 9 to 14, inclusive, for further information.

These theoretical ratios are based on the assumptions that the impressed alternating-current wave form and the counter e.m.f. wave form of the converter are both sine-waves, that there is no loss in the converter, and that the direct-current brushes are at the no-load neutral position. Variations in wave form are small in commercial circuits and apparatus. The effect of the resistance of the windings, brushes, and brush contact is appreciable, and may vary the ratios (Par. 5) from 2 to 4 per cent. Changes in brush position,

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even within the small limits permitted by commutating conditions, may affect the ratio 1 per cent. A lagging current in the converter winding has the same effect as narrowing the pole-face and will thus increase the ratio of alternating voltage to direct-current voltage. In general, therefore, actual ratios are slightly higher than the theoretical ratios (Par. 4), assuming conversion from alternating to direct-current.

4. Table of Theoretical Voltage Ratios

Number of converter phases	Ratio of alternating voltage
Single-phase	0.71 of direct voltage
Two-phase	0.71 of direct voltage
Three-phase	0.61 of direct voltage
Six-phase double delta	0.61 of direct voltage
Six-phase diametrical	0.71 of direct voltage

5. **The theoretical current ratio,** neglecting the losses and assuming 100 per cent. power-factor is the inverse ratio of the alternating and direct-current voltages (Par. 4). This follows from the equality of the alternating-current input and direct-current output. From this standpoint, but including the effect of the losses, the current ratios are given by the following formula:

$$I_a = \left(\frac{1}{Eff}\right) Y I_d \qquad \text{(amps.)} \qquad (1)$$

in which expression the symbol I_a represents the value of the alternating current and I_d the value of the direct current. Eff represents the efficiency. Y is equal to twice the square root of two divided by the number of collector-rings. Values of Y are given as follows:

No. of phases	Value of Y
Single-phase	1.41
Two-phase	0.707
Three-phase	0.940
Six-phase	0.470
(Both double-delta and diametrical transformer connections.)	.....

For all practical purposes an average efficiency of 94 per cent. may be assumed, in which case the current ratios will be as shown in Par. 6. These simple ratios are very easily remembered and are convenient for approximate calculations.

6. Table of Approximate Current Ratios

No. of phases	Alternating current per terminal
Single-phase	1.50 times direct current
Two-phase	0.75 times direct current
Three-phase	1.00 times direct current
Six-phase	0.50 times direct current

7. **Actual current ratio.** Since the current ratios given in Par. 6 are based on theoretical voltage ratios (Par. 4) the actual ratios will vary from 2 to 4 per cent. from those of Par. 6. In specific cases where exactness is desired, the current can be determined most conveniently from the direct-current output, actual alternating voltage, actual efficiency and power-factor using the following formula:

$$\text{Alternating current (per terminal)} = \frac{K.W. \times 1000}{E_a \times Eff \times Y \times P.F.} \quad \text{(amp.)} \qquad (2)$$

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Where E_a is the alternating voltage. Values of Y are given as follows:

Number of phases	Value of Y
Single-phase	1.00
Two-phase	2.00
Three-phase	1.73
Six-phase	3.00

If the efficiency and power-factor are not known, see Par. 28, 38, and 39 for probable values.

8. Armature currents and heating. The current in the converter armature may be considered as made up of: (a) an alternating current, uniformly dividing among the various conductors of the winding, which is necessary to drive the converter as a synchronous motor, and which is determined by the magnitude of the losses; (b) a current flowing from the collector-ring taps to the direct-current brushes, varying widely in value in the different conductors at different positions of the armature with respect to the field poles. The first component is small and in theoretical discussions is usually neglected. The second component for convenience in calculation, may be considered to be a resultant of the instantaneous values of alternating current and direct current in any individual conductor. Fig. 1 illustrates the

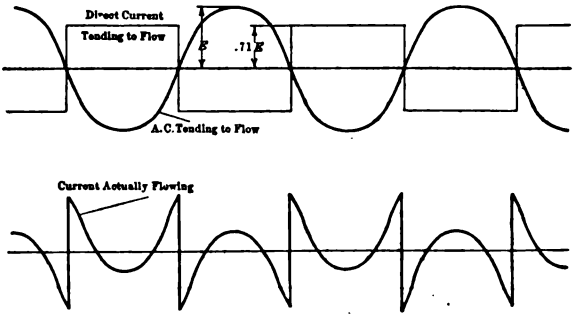


FIG. 1.—Armature current in conductor, 100 per cent. power-factor.

simplest case, namely, that of a conductor midway between alternating-current taps, which are equidistant from pole centres, and with 100 per cent power-factor alternating-current input. This diagram clearly shows the relation between the effective current actually flowing and the alternating current and direct currents that would flow in separate motor and generator windings, and indicates the fundamental reason for the economy of the synchronous converter due to its single winding.

9. The ratio of the effective or resultant armature current to the external direct current varies with the number of phases, or more properly with the number of connections per pole to the armature winding. The larger the number of such connections, the smaller will be the effective current.

10. The distribution of the current among the different conductors at 100 per cent. power-factor is such that the maximum loss occurs in the tap coils and the minimum loss in the coils midway between taps. This is shown in Fig. 3.

11. The effect of diminishing power-factor on the effective current is to increase the latter greatly, even with small reductions in power-factor. The effect of decreased power-factor on the distribution of current

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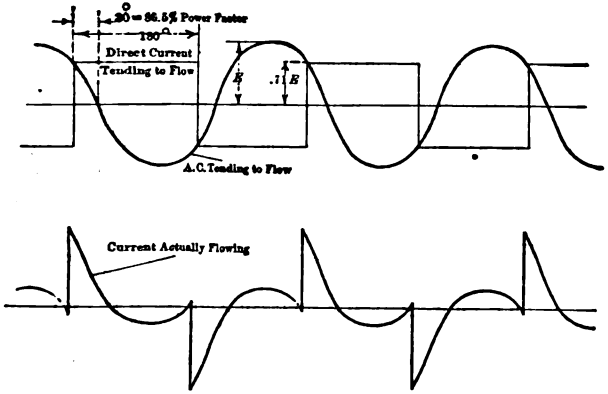


Fig. 2.—Armature current in conductor, 86.5 per cent. power-factor.

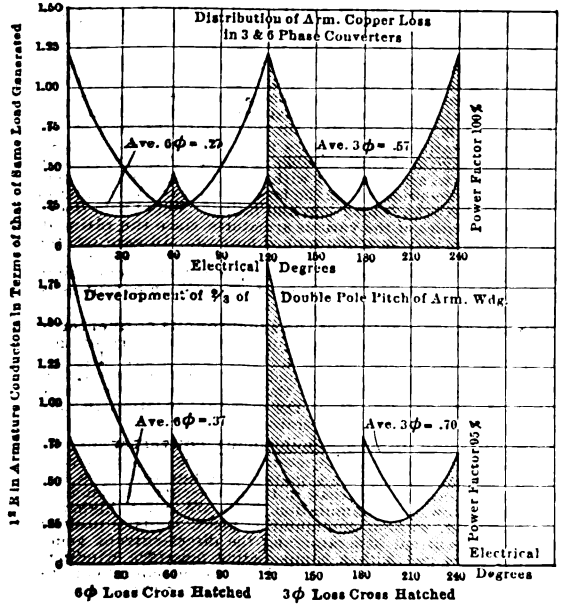


Fig. 3.—Distribution of losses at 100 per cent. power-factor and 95 per cent. power-factor.

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greatly to increase the current and loss in conductors near one side of the tap coils and to reduce the loss in conductors on the other side of the same tap coils. The average effective current and the loss are considerably increased. The effects of power-factor are illustrated by Fig. 2 which shows the same conditions as Fig. 1, except that the power-factor is 86.5 per cent. instead of 100 per cent. It will be seen that the alternating-current wave has been shifted with respect to that of the direct current, thus causing an increase in the effective current. Fig. 3 shows the difference in distribution of losses and difference in average losses with 100 per cent. and 95 per cent. power-factors.

12. Table showing Relative Converter Losses on Basis of Direct-current Generator Losses taken as Unity

Calculations based on 3 per cent. rotational losses
(Calculated by C. E. Wilson)

	Relative armature loss in complete winding					Relative maximum loss in one conductor				
No. of collector rings	P.F. 100 per cent.	P.F. 98.5 per cent.	P.F. 94 per cent.	P.F. 86.6 per cent.	P.F. 76.6 per cent.	P.F. 100 per cent.	P.F. 98.5 per cent.	P.F. 94 per cent.	P.F. 86.6 per cent.	P.F. 76.6 per cent.
2	1.451	1.522	1.734	2.160	2.940	3.121	3.653	4.358	5.342	6.808
3	0.587	0.627	0.753	1.005	1.468	1.249	1.504	2.043	2.673	3.596
4	0.391	0.426	0.532	0.746	1.137	0.751	1.017	1.367	1.861	2.596
6	0.274	0.304	0.400	0.589	0.935	0.430	0.614	0.874	1.249	1.825
12	0.209	0.236	0.326	0.500	0.824	0.249	0.354	0.525	0.792	1.232

13. Losses affecting rating. Par. 12 shows the relative average losses and maximum loss per conductor compared with those of the equivalent direct-current generator for various phases and power-factors. It shows a large increase, particularly in the maximum loss due to small changes in power-factor. It is this characteristic that limits the use of synchronous converters to operating power-factors near 100 per cent. This table also shows the advantage of a large number of rings. Practically all converters above 200 or 300 kw. are now built with six collector-rings and phases, while 12 rings have been considered for the largest ratings. A distinction must be made, however, between copper loss and rating. This table does not represent relative capacities of the various armatures, since the rating depends on many other factors besides armature coil heating. In general, the **current capacity** of a given armature will be increased by increasing the number of rings and will be reduced by a reduction in power-factor, even slightly below 100 per cent. power-factor, although not to so great an extent as is indicated by a direct comparison of the losses.

14. The armature reaction of the synchronous converter is relatively small compared with that of the equivalent direct-current generator on account of the relatively small effective armature current. In this characteristic the converter is very nearly equal to the compensated direct-current generator. In a six-phase converter, the effective armature reaction varies from 7 per cent. to 20 per cent. of the armature reaction in an equivalent uncompensated direct-current generator.*

15. Commutation in the synchronous converter offers the same problem as in the direct-current generator, differing only in degree. Due to the smaller effective current the armature reaction and, to a lesser extent, the self-induction, are smaller than in the direct-current generator of equal rating, so that allowable commutation limits are much higher. The synchronous converter, without commutating poles, holds a position between the simple direct-current generator and the direct-current generator with commutating poles and with a compensating pole-face winding. For this reason the commutating poles with their attendant complications were not added to the synchronous converter until long after they had been success-

* Lamme, B. G. and Newbury, F. D. "Interpoles in Synchronous Converters;" *Trans.* A. I. E. E., Vol. XXIX, page 1625.

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fully used with direct-current generators and motors. During the past 2 years, however, this refinement has been added to the synchronous converter and considerable gains have been made due to its use. In the synchronous converter the commutating-pole winding has approximately 25 per cent. to 40 per cent. of the ampere-turns which are necessary in the equivalent direct-current generator.*

16. **The relation between power-factor and main field excitation** is the same in the synchronous converter as in the synchronous motor or in synchronous generators in parallel. For reasons already stated (Par. 11, 12, and 13), the synchronous converter is not used for operation at low power-factor except at small loads, so that this question is not of practical importance.

17. **Control of direct-current voltage.** Due to the fixed ratio between the alternating voltage and the direct-current voltage, variation in direct-current voltage can be obtained only by three general methods, which are as follows: (a) by varying the alternating voltage; (b) by varying the direct-current voltage; (c) by varying the flux without correspondingly varying the alternating voltage, as in the split-pole converter.

18. **For varying the alternating voltage,** the important commercial methods are: (a) by an induction regulator or regulating transformer; (b) by a synchronous booster; (c) by the combined action of reactance and series field winding.

19. **A regulating transformer** (also called a Stillwell regulator) consists of a transformer with a large number of taps and a dial face plate for connecting the converter terminals to the various transformer taps. The transformers and switching devices are large and expensive, and the switches are subject to rapid deterioration due to sparking while changing the voltage.

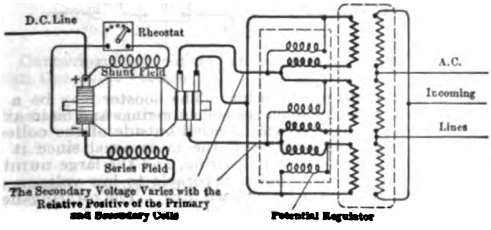


FIG. 4.—Connections of synchronous converter and induction regulator.

The method also has the objection that the voltage cannot be varied by small increments unless an excessive number of taps is provided. In the past this method has been used extensively but, with the development of preferable methods, has been abandoned. An **induction regulator** accomplishes the same result with infinitely small increments and without interrupting the electrical circuit. The induction regulator consists of a stationary winding (usually the secondary) and a rotatable winding (usually the primary), the change in voltage being obtained by rotating one element through part of a revolution, which changes the ratio of the secondary and the primary voltages. It is simply a polyphase transformer with rotatable primary. The connections are shown in Fig. 4. Through suitable relays the alternating voltage may be changed automatically or from a distance. The disadvantages of this method of regulation are the additional floor space and complicated wiring required and the difficulty of designing the induction regulator to withstand the mechanical stresses incident to connecting the converter to the line slightly out of step, and also to withstand short circuits.

20. **The synchronous booster converter** consists of the combination of an ordinary converter with an alternating-current generator having the

* Lamme, B. G. and Newbury, F. D. "Interpoles in Synchronous Converters;" *Trans.* A. I. E. E., Vol. XXIX, page 1625.

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same number of poles as the converter and having its armature windi connected in series with the converter armature winding. This boos alternator, by a change in its own excitation, varies the voltage applied to t terminals of the converter. The excitation is so arranged that the boos fields and voltage may be reversed without opening the field circuit. T possible variation in voltage is double the rated booster voltage, since it m be added to or subtracted from the line voltage. The connections are sho in Fig. 5. The voltage may be controlled automatically through relays a regulator, or the booster may be series wound, thus automatically compoun ing the converter. This method of voltage variation has largely superseded the methods previously described, particularly in the larger installations.

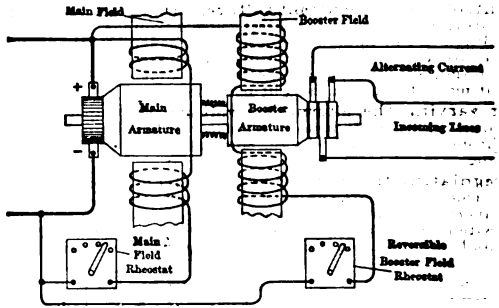


FIG. 5.—Synchronous booster converter.

21. Types of synchronous booster. The booster may be a revolvin armature generator located between the collector-rings and main armature, it may be a revolving-field generator located outside of the collector-ring The revolving-armature construction is the more usual since it eliminat additional collector-rings and external wiring, and the large number of pa allel circuits in the converter winding favorable to low-voltage generatio may be conveniently used in the booster winding. The rotating-field boost is sometimes preferable since it may be added to a standard converter wi less change in existing parts. There is also less interference with the ve tilation of the main armature.*

22. The application of commutating poles to the booster convert involves new features due to the motor action, or the generator action, of t converter when the booster is excited. The converter acts as a motor to t extent of the booster output plus all losses, when the booster is excited increase the direct-current voltage, and, conversely, the converter acts as generator to the same extent when the booster is excited to lower the voltag Due to this motor or generator action the effective current in the convert armature varies with the booster excitation as well as with the output of d rect current.† If the effective armature current varies, the commutatin pole flux must vary correspondingly if the commutating poles are to be benefit. This variation is accomplished by providing two windings on t commutating poles: A series winding that provides the correct excitatio when the booster is not excited; and a shunt winding in which the current varied, in amount and direction, in proportion to the change in armatu reaction caused by the booster. There are numerous methods used in pra tice to control the current in the shunt winding of the commutating pole

* Newbury, F. D. "Voltage Regulation of Rotary Converters;" *Electr Journal*, Vol. V, page 616.

† Yardley, J. L. McK. "Efficiency of Synchronous Booster Co verters;" *Elec. Journal*, Feb., 1913.

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One of the simplest consists in connecting the shunt commutating pole winding across a double-dial "potentiometer-type" rheostat, which is mechanically connected to a similar rheostat that controls the booster field excitation. Any change in booster excitation causes a corresponding change in commutating pole excitation. The commutating pole excitation is further controlled by connecting a resistance in series with the field winding that is varied automatically in proportion to the direct-current load on the converter.*

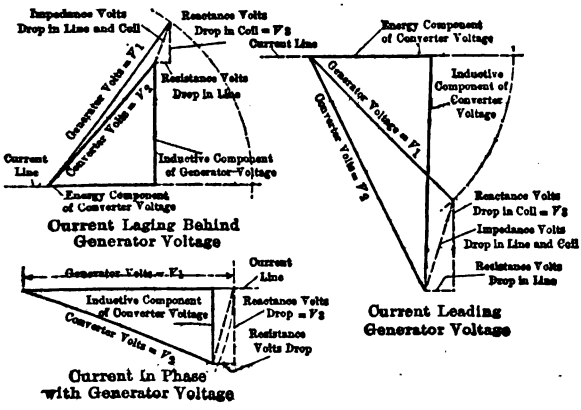


FIG. 6.—Variation of converter voltage with reactance in circuit and with varying power-factor.

23. Automatic compounding. With reactance in the supply circuit of the converter, the voltage at the collector-rings may be varied through a small range by changing the phase of the supply current. As previously explained, the current phase may be altered by varying the excitation of the main field winding. In practice this is accomplished automatically by providing a series-field winding in addition to the shunt-field winding. The direct-current voltage is varied in the compound-wound converter by the combined effect of the series winding and the reactance in producing a variation of the alternating voltage. While the arrangement of field windings is the same as in the compound-wound direct-current generator, the theory and the action are entirely different. The effect of the reactance in varying the voltage may be seen from the diagrams in Fig. 6. At lagging power-factors the reactance voltage diminishes the line terminal voltage and at leading power-factor it increases the line terminal voltage.†

24. Heating effect of automatic compounding. On account of the additional heating at power-factors less than unity, it is customary to operate at low lagging power-factors at light load (when the additional heating is of no consequence) and at leading power-factors only slightly below 100 per cent. at overload.

* A detailed description of this method of control will be found in an article by M. W. Smith, "Commutating Pole Windings of a Synchronous Booster Converter," *Elec. Journal*, Dec., 1917.

† Lincoln, P. M. "Voltage Regulation of Rotary Converters;" *Elec. Journal*, Vol. I, page 55.

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25. Conditions affecting direct-current voltage regulation the compound converter.* It is apparent that the direct-curre voltage regulation of the compound-wound converter depends on mai elements internal and external to the converter, and that the chan in voltage is limited by the inability of the converter to operate low power-factor and heavy load. The range of voltage is more r stricted and the results are much more difficult to predetermine tha in the compound-wound direct-current generator. The voltage ran is affected by certain factors which are as follows: (a) the resistan drop between the point of constant voltage and the converter; (b the reactance drop between the same points; (c) the ratio of armatu ampere-turns to shunt-field ampere-turns; (d) the ratio of series-fiel ampere-turns to shunt-field ampere-turns; (e) the setting of the shun field rheostat; (f) the transformer secondary voltage; (g) the total dro through the converter.

26. Customary values for these factors (Par. 25) are as follows: (a) th full-load armature ampere-turns are approximately equal to the no-load shun field ampere-turns; (b) the full-load series-field ampere-turns are approximatel one-third the armature or shunt-field ampere-turns; (c) the shunt-fiel rheostat is so set that the lagging component of the line current will b approximately 25 per cent. of the full-load energy component; the shunt field current will then be about 50 per cent. of its normal no-load 100 pe cent. power-factor value under the previous assumptions; (d) the transforme secondary voltage is chosen higher than the correct no-load value to com pensate for the under excitation of the shunt field.

Under the above conditions, an approximately flat direct-current voltag regulation curve will be obtained from no load to full load with constan voltage at the high-tension transformer terminals and 15 per cent. reactanc in the transformer. It is impossible to over compound the converter (o compensate for alternating-current line drop) unless the series field strengt and the reactance are considerably increased.

27. Relation between power-factor and load in compound converters. With the average conditions stated in Par. 26, the power-factor will vary with the load approximately as is shown, Par. 28. With larger overloads—carried for a sufficient length of time to make heating a consideration—the shunt field winding should be further under-excited in order to bring the power-factor nearer unity at the extreme overloads, or the series field should be shunted to reduce the change in power-factor with load.

28. Table of Power-factor Variation with Load in Compound Converters

Load	Power-factor
	Per cent.
¼	40 lag
½	65 lag
¾	92 lag
⅞	98.5 lag
Full	100 per cent.
1¼	99 lead
1½	98.5 lead

29. The reactance necessary for compounding may be in the ste down transformers or in separate reactance coils. Where possible, t transformers are designed with the necessary reactance, as this method

* Bache-Wiig, J. "Voltage Regulation of Compound-wound Rotary Co verters;" *Elec. Journal*, Vol. VIII, page 860.

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lower in cost and requires less floor space and wiring; it is, however, difficult so to design the transformers when the required reactance is more than 10 per cent. It is also more difficult to obtain high reactance in 25-cycle than in 60-cycle transformers, and in the core type than in the shell type (Sec. 6).

30. The split-pole method of voltage control utilizes a different principle from any previously discussed. Variation of direct-current voltage is secured, not by a variation in the impressed alternating voltage, but by a change in the shape of the magnetic field, such that the total flux and the direct-current voltage are changed, while the alternating voltage remains substantially unchanged. This is possible because of the fact that in polyphase windings in which the phases are tapped 120 electrical degrees apart, third harmonics and multiples thereof cancel out and do not appear at the 120-deg. terminals. The action of the split-pole converter therefore depends on variations in the field flux distribution which produce third harmonics, in conjunction with taps on the alternating-current side 120 deg. apart. The reason for this will be understood by reference to Fig. 7. It is evident that the armature coils between the 120-deg. taps on the alternating-current side will always include two equal and opposite areas of the third-harmonic variation of flux which neutralise each other and so produce no change in alternating-current wave form. On the other hand, the armature coils between the brushes on the direct-current side, which are 180 electrical degrees apart, will always include three areas of the third harmonic variation in flux, only two of which neutralise each other, leaving one to change the average ordinate of the field flux curve, and, consequently, the direct-current voltage.

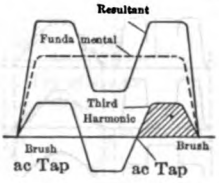


FIG. 7.—Flux distribution in three-part pole, split-pole converter.

With the split-pole converter, the 120-deg. connection on the alternating-current side is preferable; consequently the three-phase delta connection or the six-phase double-delta connection should be used. However, any secondary connection of transformers may be used providing the primary is Y connected and the neutral is not fixed.

Harmonics other than the third and multiples thereof will appear at the alternating-current terminals and will cause a corrective current to flow from the supply circuit through the converter windings so as to neutralise the flux producing these harmonics in the converter. It is desirable, therefore, so to design the converter that the wave form will be as nearly as possible a combination of the fundamental, third and ninth harmonics. In practice this is so nearly accomplished that the effect of the split-pole converter on the supply circuit wave form is negligible.*

31. Action of the split-pole converter. When the split-pole converter is operated at a higher voltage than that corresponding to the alternating line voltage, the additional output due to the increased direct-current *voltage* is supplied by an increased *current* on the alternating-current side. This current moreover is a "motor" current dividing in the converter in the same way as the motor current necessary to supply the losses. The value of the effective current is, therefore, considerably increased. At lower voltages the converter acts as an alternating-current generator decreasing the line alternating current, but due to the distribution of the current in the armature the effective current is increased.

32. Two types of split-pole converter. The first converters of this type were designed with two regulating poles for each main pole. This arrangement resulted in symmetrical flux and voltage wave forms through-

* (a) Stone, C. W. "Some Developments in Synchronous Converters;" *Trans.* A. I. E. E., Vol. XXVII, p. 181.
(b) Steinmetz, C. P. "Variable Ratio Converters;" *G. E. Review*, 1908, pages 26–84, 1909.
(c) Burnham, J. L. "Modern Types Synchronous Converters;" *G. E. Review*, page 74, 1912.

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out the entire voltage range, and was favorable to commutation but required machines of comparatively large diameter. The split-pole converters as built at present have a single regulating pole for each main pole. This construction obviously permits a considerable reduction in diameter and cost for a given output, and the detrimental effect of the varying magnetic field in the commutating zone can be compensated for by providing favorable commutating conditions in other respects. The field-flux wave forms and the corresponding voltage wave forms for various voltages, with both the three-part pole and the two-part pole constructions, are shown in Fig. 8.

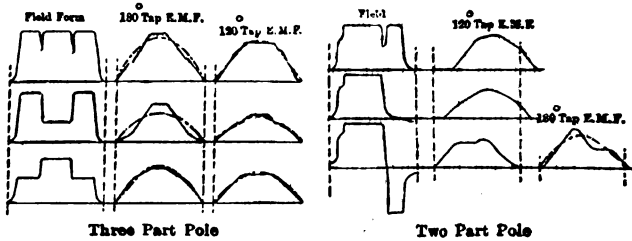


FIG. 8.—Flux-distribution and alternating voltage wave forms in split-pole converter.

Upper curves, max. voltage. Middle curves, mid. voltage. Lower curves, min. voltage.

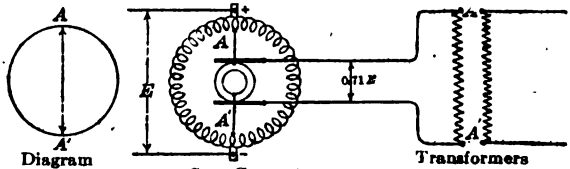


FIG. 9.—Single-phase connections.

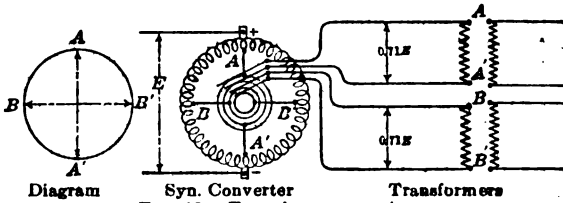


FIG. 10.—Two-phase connections.

33. Limits of voltage variation with the split-pole converter. In varying the voltage, the excitation of the regulating poles is increased in the same direction as the excitation of the main poles to increase the voltage, and is reversed to decrease the voltage. The split-pole converter is limited to approximately 20 per cent. variation in either direction, but this is sufficient to cover the majority of applications.

34. Direct-current booster.—The direct-current voltage can be varied directly by inserting a booster in the direct-current circuit. This booster may be direct-connected to the converter or driven by a separate

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motor. It is generally used in the latter form as an addition to existing equipment, since it does not affect the converter either structurally or in respect to operating voltage. All methods involving change in alternating voltage necessitate the operation of the converter at the highest voltage.

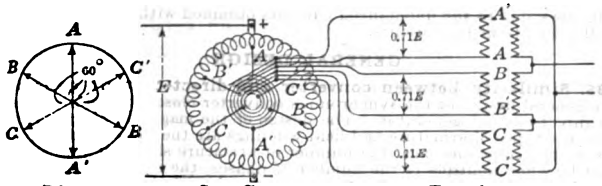


FIG. 11.—Six-phase diametrical connections.

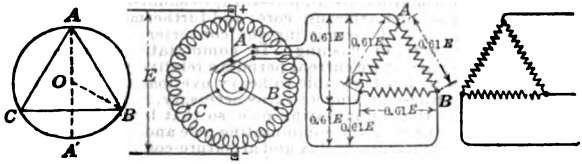


FIG. 12.—Three-phase delta connections.

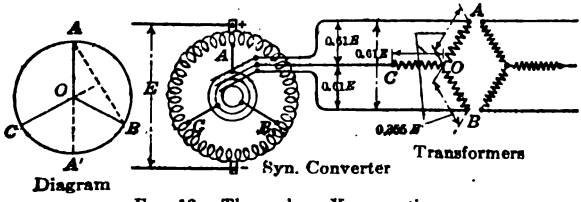


FIG. 13.—Three-phase Y connections.

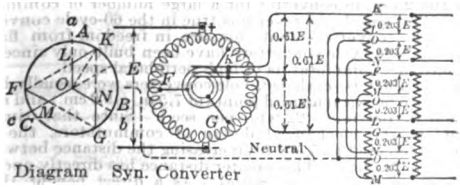


FIG. 14.—Three-phase interconnected Y connections (for 3-wire direct-current circuits).

The weight, floor space and cost of a converter with a direct-connected direct-current booster are greater than the same factors in a converter with an alternating-current booster. A further serious disadvantage of the direct-current booster is the additional commutator, which is equal in current capacity to the converter commutator.

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35. Transformer voltages and connections. The various tra former connections with voltages commonly used are shown in Figs to 14, inclusive. Fig. 14 shows the transformer connections necessa when the converter is used to supply three-wire direct-current circu this modification in the transformer windings is necessary to avoid magne unbalance due to the unbalanced currents obtained with unbalanced loa on the direct-current circuits.

GENERAL DESIGN

36. Similarity between converter and direct-current generator. The general design of the synchronous converter closely resembles that o the direct-current generator. The design of the magnetic circuit is iden tical; the types of armature and field windings are the same, except for th taps to the collector-rings; the number of armature slots per pair of pol must be some multiple of the number of phases; the design of the electri circuit is the same, except for the reduced value of the effective curren This reduction of effective armature current permits smaller conductor and smaller armature slots—a condition favorable to commutation; it also permits a higher ratio of armature ampere-turns to shunt-field ampere-turns resulting again in a smaller armature core; and furthermore, it reduces the flux distortion on overload, permitting the converter to carry large mo mentary overloads without flashing. In commutating-pole converters the reduced effective armature current permits a relatively small commutat ing-pole winding, which is favorable to heavy overloads. With the small number of commutating-pole ampere-turns necessary, it is easy to provide sufficient section in the commutating pole so that large overloads can be carried without saturating the commutating pole and thus destroying the equivalence of commutating-pole flux and armature-coil flux. In the direct current generator this is not true, and commutating-pole saturation is usually a limit to the overloads that can be carried.

There are, however, various requirements in design, due to the rigid relationship between poles and speed, that do not enter into direct-current generator design. Following directly from this relationship, the maxi- mum distance between adjacent neutral points on the commutator of any synchronous converter is a direct function of the frequency and the pe- ripheral speed of the commutator. The peripheral speed of the commutator, in feet per min., is equal to the alternations per min. (cycles per sec. times 120) multiplied by the distance in feet between adjacent neutral points on the commutator surface.

37. Comparison between 25-cycle and 60-cycle converters. This simple relationship between poles and speed (Par. 36) is responsible for most of the difference between high-frequency and low-frequency con- verters. It follows from this law that the distance between neutral points in a 25-cycle converter is 2.4 times the distance in a corresponding 60-cycle converter for the same commutator speed. Thus while ample room is available in the 25-cycle converter for a large number of commutator bars at a low peripheral speed, the reverse is true in the 60-cycle converter. The 600-volt 60-cycle converters that compare in freedom from flashing and sensitiveness with 25-cycle converters have been built only since it became possible to construct commutators of high peripheral speed.

Up to the year 1909, 60-cycle 600-volt converters were usually built with a maximum distance between neutral points of 7.5 in. (19.0 cm.) and a peripheral speed of 4,500 ft. per min. (22.9 m. per sec.). Since that time, through improvements in the mechanical design of commutators, the peripheral speed has been increased to 5,500 ft., increasing the distance between neutral points to 9 in. (22.9 cm.). This greater distance has directly and indirectly improved the operating characteristics. As a direct benefit there is less chance that a flash under a brush will reach to the adjacent brush arm, caus- ing the converter to buck; and, indirectly, the greater distance permits the use of more commutator bars, reducing the maximum voltage between bars and so reducing the danger of an arc spreading from bar to bar. With 9 in. (22.9 cm.) available between neutral points, it is possible to proportion 60- cycle converter commutators much more conservatively than was possible in older designs with resulting improvement in performance.

The distance between neutral points becomes a design limitation only with

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the higher line voltages. At 250 volts the design of the 60-cycle converter has not been handicapped as it was at 600 volts, although it has unjustly suffered in reputation. During the past five years 60-cycle converters have practically displaced motor-generator sets for 250-volt lighting and industrial power service.

18. Table of Weights, Speeds and Efficiencies for 600-volt, 25-cycle and 60-cycle Converters

Kw.	Frequency	R.p.m.	Approximate net weight (lb.)	Approximate efficiency at full load, per cent.
*300	25	750	10,100	95.3
*500	25	750	15,000	96.0
*1,000	25	750	23,000	96.5
1,500	25	500	38,000	96.7
2,000	25	375	58,000	96.7
3,000	25	250	92,000	96.8
4,000	25	214	102,000	96.8
*300	60	1,200	7,000	95.0
*500	60	1,200	10,000	95.3
*750	60	1,200	14,000	95.5
*1,000	60	900	19,500	95.7
1,500	60	720	28,000	96.0
2,000	60	450	46,000	96.0
3,000	60	400	69,000	96.2

19. Table of Weights, Speeds and Efficiencies for 250-volt, 25-cycle and 60-cycle Converters

Kw.	Frequency	R.p.m.	Approximate net weight (lb.)	Approximate efficiency at full load, per cent.
300	25	750	12,000	95.0
500	25	750	15,500	95.2
750	25	750	21,000	95.3
1,000	25	500	29,000	95.5
2,000	25	300	65,000	95.7
100	60	1,200	3,100	93.1
150	60	1,200	3,800	93.6
200	60	1,200	4,500	94.0
300	60	1,200	6,600	94.0
500	60	1,200	12,000	94.5
1,000	60	900	21,000	94.8
1,500	60	600	36,000	95.3

Table of Weights, Speeds and Efficiencies for 250-volt, 25-cycle and 60-cycle Booster Converters

Kw.	Frequency	R.p.m.	Approximate net weight (lb.)	Approximate efficiency at full load, per cent.
1,000	25	500	35,000	95.0
2,000	25	300	73,000	95.1
4,000	25	167	174,500	95.3
500	60	1,200	14,000	94.3
1,000	60	900	24,000	94.5
1,500	60	600	41,000	95.0
2,000	60	450	60,000	95.2
3,000	60	300	105,000	95.4

* Will stand 200 per cent. overload momentarily—all other machines will stand 100 per cent. momentary overload.

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The efficiencies given in Par. 38 and 39 are those calculated from separately measured or calculated losses as prescribed by A. I. E. E. Standards for conventional efficiencies. (See Par. 94.)

40. Commutator design for synchronous converters follows that for direct-current generators except that long high-speed commutators are more frequently used. The longest commutators are built with three V-ring supports, or with two V-ring supports and a central shrink ring. Shrink rings alone are not as effective as either of these constructions for the majority of cases, on account of the large diameters involved. With large diameters, large tangential stresses are produced in the shrink ring by relatively small radial forces. The V-ring construction without shrink rings is generally to be preferred since the commutator can be readily taken apart for repairs and also can be more easily insulated from adjacent parts. A construction embodying four V-rings has been employed to a limited extent; this consists, in effect, of two separate commutators flexibly connected together. The inaccessibility of the middle V-rings is a serious objection to this construction.

Long commutator necks must be braced from each other. This is done by fibre plugs set into each neck, by interlacing heavy twine between the necks, or by roping wooden spacing blocks to each neck.

41. The ventilation of commutators, in cases where the necks do not provide sufficient cooling surface and windage, has been most successfully accomplished by attaching radiating vanes about 2 in. square to the outer end of each bar. These vanes not only provide additional cooling surface at the most effective point, but considerably increase the air circulation.

42. Armature equalizer connections are used in synchronous converters just as in direct-current generators (Sec. 8) to equalize the effect of the flux under all poles. The collector-rings are also equalizing rings, so that the equalizers are usually spaced with respect to the collector-rings. To secure greater accessibility, the equaliser rings are generally located on the collector end of the armature. Special constructions have been developed in order to place the equalizing connections in such a manner that there will be no interference with the collector connections and no increase in the length of the commutator.

43. Damper windings. Almost without exception synchronous converters are provided with damper or **amortisseur windings** to prevent hunting (Par. 61). These are usually of the built-up grid type, commonly employed on the rotors of induction motors, consisting of a large number of bars located in slots in the pole-face, and connected on the ends by continuous rings. A cast-copper damper winding is sometimes employed, consisting of relatively few bars of large cross-section in the pole face. In the commutating-pole converters, the end rings are sometimes made in disconnected segments—one for each pole—so that the commutating poles will not be enclosed by the damper winding. If the commutating poles are individually enclosed, changes in the commutating-pole flux are damped, thus preventing the commutating-pole flux from changing as rapidly as the armature current and flux when sudden changes in load occur.

44. The machine ventilation problem varies widely in converters for different frequencies and voltages. In high-speed 25-cycle converters of medium output, the armatures are small in diameter and relatively long. Every means is used to increase the natural air circulation. In these machines, heating and commutation are of approximately equal effect in limiting the output. In large 25-cycle converters of both voltages (250 and 600) and in 60-cycle converters for 250 volts, the natural air circulation is ample for the dissipation of the losses, but not excessive. In 60-cycle 600-volt converters and particularly in those of large size, the armatures are of large diameter and narrow, and the peripheral speeds are high. Under these circumstances, the natural air circulation is much greater than is necessary and greatly increases the windage loss. In such machines the natural air circulation is restricted as much as possible by stopping the air entrances in order to eliminate the unnecessary windage loss.

CHARACTERISTICS

45. The no-load saturation curves are very similar to the same curves for direct-current generators. There are two such curves—one with direct-

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current volts and one with alternating volts as ordinates. From these curves the actual no-load voltage ratio may be determined for any desired voltage.

46. Heating of synchronous converters occasions practically no difficulty either in design or in operation under proper conditions of power-factor, etc. The problem, however, varies with converters of different frequencies and voltages (Par. 44).

47. The overload capacity, as determined by heating and by flashing, is inherently large, due in great measure to the small armature reaction. The latter is particularly important since it results in small field distortion due to load. Consequently, on sudden changes in load, there is very little increase in voltage between commutator bars or shifting of the flux in the commutating zone, both of which, if present, would tend to cause flashing.

48. The losses may be divided into constant losses (with varying load) and variable losses. The constant losses are: core loss; friction and windage losses (including commutator and collector friction); and shunt field and rheostat loss (assuming that rheostat resistance and direct-current voltage remain fixed). The variable losses are: armature copper loss; series-field copper loss; commutating-field copper loss; brush I^2R and surface-contact losses; and load loss.

49. Additional losses in the synchronous booster converter. In the synchronous booster converter, the only additional losses at the mid-voltage are the booster armature copper loss and the load loss. At higher voltages, the converter copper loss is increased due to the larger "motor" current and the core loss is increased due to the higher voltage. At lower voltages the converter core loss is reduced, since the flux is reduced; the converter copper loss is increased due to the larger "generator" current, and the booster losses are the same as for a corresponding increase in voltage.

50. Additional losses in the split-pole converter. In the split-pole converter there are no additional losses at the mid-voltage, but at either lower or higher voltages the converter core-loss is increased, since the flux density is increased (Par. 32 and Fig. 8). The converter copper loss is increased, as in the booster converter, at higher and lower voltages (Par. 31).

51. Hunting of synchronous converters, as in other forms of synchronous apparatus, is the periodic variation of the rotor from the true synchronous position with respect to the supply system. * During hunting, the rotor is alternately ahead and behind its true synchronous position. In forging ahead, energy is expended in the converter, the latter acting as a motor; in dropping behind, the converter acts as a generator and gives up energy. This alternate motor and generator action is accompanied by a variation in the value of the flux due to the armature reaction, by a fluctuation of alternating-current and power-factor, and by a shifting of the commutating field which causes periodic sparking at the brushes. The frequency of the hunting cycle may often be determined from the frequency of the sparking. Hunting may be caused by periodic variation in the supply frequency, by sudden changes in load, or by excessive line drop. It is more likely to occur in 60-cycle than in 25-cycle converters, because of the greater number of poles and consequently smaller actual angular variation corresponding to the limiting electrical angular variation. *

52. Hunting may be practically eliminated by providing suitable **damper** or **amortisseur windings** in the pole faces. Since hunting is accompanied by a shifting of the flux across the pole face, the winding placed in the path of this flux will oppose any such change, and will tend to damp out the oscillations as soon as they begin. Practically all converters are now built with such windings (Par 43). Hunting troubles have also been greatly reduced by the use of generators driven by steam turbines or water turbines in which the angular velocity is much more uniform than in reciprocating engines.

53. Interruption of energy supply. If a converter is operating alone

* (a) Steinmetz, C. P. "Hunting;" *G. E. Review*, May, 1913.
(b) Newbury, F. D. "Hunting of Rotary Converters;" *Elec. Journal*, June, 1904.
(c) Lamme, B. G. "Causes of Hunting;" *Elec. Journal*, June, 1911.

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or in parallel with other converters supplied from the same alternating-current feeders, the interruption of the alternating-current supply will bring the voltage on the direct-current side to zero, and the converters will stop. If, however, there is another source of direct-current connected to the same direct-current bus and not dependent on the same alternating-current feeders, interruption of the alternating-current supply will not cause the converter to stop; the direct-current voltage will be maintained and the converter will be driven as an inverted converter. If the shunt field happens to be weak or is interrupted, or if the converter should supply energy to an inductive load on the alternating-current side (such as a short-circuit on the high-tension side of the transformers) the speed will greatly increase. To guard against danger under such conditions, converters are usually provided with a speed-limit device, and the alternating-current and direct-current breakers are so interlocked that opening the alternating-current breaker opens the direct-current breaker. In addition, the direct-current breakers are sometimes provided with a reverse-current tripping relay. When the alternating-current supply is subject to serious drop in voltage due to short-circuits or other cause, it may be advisable to provide the alternating-current breakers with low-voltage tripping coils. This is particularly necessary with commutating-pole synchronous converters due to the flashing that would occur should the converter drop out of step as a result of low voltage, and later start with the brushes down when the voltage resumes normal value.

54. The speed-limit device (Par. 53) consists of a pivoted weight rotating with the converter shaft; the centrifugal force acting on the weight is counter-balanced by a spring. The weight moves outward and operates a switch when the predetermined overspeed is reached. The switch closes (or opens) the circuit of the shunt tripping coil of the direct-current breaker.

GENERAL APPLICATIONS

55. Comparison of efficiency with that of a motor-generator set. The efficiency of a 60-cycle converter including its transformers will be from 3 per cent. to 5 per cent. higher than an equivalent synchronous motor-generator set without transformers. The 25-cycle converter shows a further gain in efficiency over the motor generator set of from 0.5 to 1.0 per cent. If the line voltage is above 13,200 volts, transformers will usually be required with the motor-generator set as well as with the synchronous converter, so that the difference in efficiency in favor of the latter will be further increased by 2 per cent. This higher efficiency of the converter is such an important advantage that it is sufficient alone to justify the use of synchronous converters wherever possible.

56. Comparison of required floor space with that of a motor-generator set. The floor space required by 60-cycle converters and transformers is approximately equal to the floor space required by 60-cycle motor-generator sets of compact design. The fact, however, that the transformers may be placed in some remote location makes the arrangement of synchronous converters and transformers more flexible and gives them in many cases the advantage of reduced floor space.

57. Comparison of cost with that of a motor-generator set. The combined cost of synchronous converters and transformers is approximately equal to the cost of synchronous motor-generator sets without transformers, assuming a motor voltage of 2,300 volts or lower. For higher alternating voltages the motor cost increases appreciably, making the comparison favorable to the converter equipment. With alternating pressures above 13,200 volts, transformers are necessary with the motor-generator set as well as with the synchronous converter, so that the cost of the converter equipment is relatively still lower. With 60-cycle apparatus under 200 kw. capacity and alternating voltages of 2,300 volts and lower, the comparison is somewhat in favor of the motor-generator set, while with larger apparatus the comparison is somewhat in favor of the synchronous converter. In few cases, however, will there be sufficient difference in cost alone to determine the choice of the apparatus.

58. Comparison of reliability with that of a motor-generator set. The design and construction of synchronous converters has been standardised to such an extent that in respect to reliability the comparison is mainly concerned with the number of machines involved. Compared with a three-

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unit motor-generator set consisting of a synchronous motor, direct-current generator and direct-current exciter, the single unit converter has a decided advantage. The comparison between the motor-generator set and the booster converter is apparently less favorable on account of the additional booster generator, but there are so few troubles that can reasonably be expected in a relatively small low-voltage alternator that the difference is more apparent than real.*

59. Comparison of voltage control with that of a motor-generator set. In this characteristic the synchronous motor-generator set has an advantage over the synchronous converter. The independence of alternating and direct-current voltage in the motor-generator set may justify its use on alternating-current circuits in which the voltage fluctuates badly and where it is essential to maintain steady direct-current voltage. Even under such conditions of fluctuating alternating voltage it is considered preferable, by some engineers, to employ the converter and obtain the desired steady direct-current voltage by means of a regulator.†

60. Comparison of power-factor control with that of a motor-generator set. The motor-generator set, including a synchronous motor, may be designed to correct power-factor more economically than can the synchronous converter. For this reason, the motor-generator set is usually employed where considerable power-factor correction is necessary.

61. For railway service compound-wound synchronous converters are generally used, sufficient reactance being placed in the alternating-current supply circuit to obtain the necessary voltage regulation. For this service on 25-cycle systems, synchronous converters are used to the practical exclusion of motor-generator sets and other forms of conversion apparatus. On 50-cycle and 60-cycle systems, the use of motor-generator sets, and in Europe the use of motor converters has, in the past, been more general; but even for these higher frequencies the use of the synchronous converter has become general.

62. For lighting and power service, the shunt-wound converter with induction regulator or the more specialized form of booster converter is used. On the larger 25-cycle systems, the use of converters is general. On 60-cycle systems, their use, particularly in the booster form, is rapidly growing, due mainly to the gain in efficiency. Very few motor-generator sets are now being installed for this service.

63. The synchronous converter can be used to supply 3-wire direct-current circuits without any structural change, except in the case of compound-wound or commutating-pole converters, in which the series windings on alternate poles are connected in the positive and negative leads so that unequal currents in these leads will not affect the magnetization of the converter. See Par. 35 and Fig. 14 for the transformer connections necessary to obtain the neutral lead. The synchronous converter will operate under extreme differences of current value in positive and negative leads with very small differences in voltage between the outside leads and the neutral lead. For example, a 1,000-kw., 60-cycle, 280-volt commutating-pole booster converter, operated with full-load current in the positive lead and half-load current in the negative and neutral leads, had a difference of only 1 volt in the pressures from neutral to positive and neutral to negative leads. The same converter, operated with full-load current in the positive and the neutral leads and zero current in the negative lead, had a difference of 4 volts in the pressures from neutral to positive and neutral to negative leads. Without the resistance drop of the booster armature winding, the voltage balance would have been still better.

64. For electrolytic work, either shunt-wound converters without means for varying the voltage, or the same types of variable voltage converters as used for lighting service, are generally employed.

OPERATION

65. Alternating-current self-starting. The synchronous converter may be started as an induction motor if alternating current at reduced vol-

* Lincoln, P. M. "Motor Generators versus Synchronous Converters;" *Proc.* A. I. E. E., March, 1907.

† Walker, Miles. "Rotary Converters versus Motor-Generators;" *Jour.* I. E. E. (London), Discussion, Vol. XXXVIII, page 428.

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tage is applied to the collector-rings. The armature winding acts as the primary and the squirrel-cage winding imbedded in the pole faces acts as the secondary. For the smaller converters one starting voltage only is required. The middle terminals of a double-throw switch are connected to three of the collector-rings, one set of outer terminals is connected to the starting-voltage taps of the transformers and the other set of outer terminals is supplied with the full voltage of the line. With six-phase converters three leads are carried direct from the transformer to the converter, and three through the main and

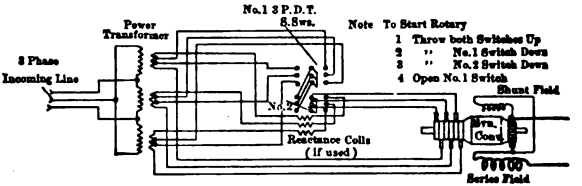


FIG. 15.—Alternating-current self-starting connections with two starting voltages.

starting switches. With the largest converters, it is usual to employ two starting voltages for which two double-throw three-pole switches are required. The connections for this arrangement are shown in Fig. 15.

66. Field "break-up" switch. During the starting period the field winding has voltages induced in it of magnitudes depending upon the ratio of armature and field turns. To prevent a dangerous induced voltage in the field winding, the field circuit may be opened in several places during the starting period by means of a multi-point double-throw switch, which is usually located on the frame of the converter. Appreciable voltage rise in the field circuit may also be prevented by closing the field circuit during start-

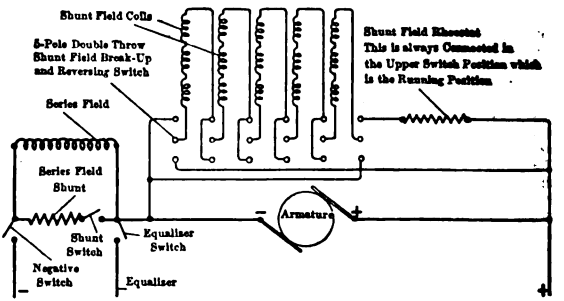


FIG. 16.—Converter connections on direct-current side (alternating-current self-started).

ing. This method is employed generally because it only requires a double-pole double-throw field switch which may be conveniently located on the starting panel adjacent to the main switch.

67. Series-field switch. If a series-field shunt is used, a switch is usually provided for opening the closed circuit formed by the series field and its shunt. If this low-resistance circuit were left closed, the single-phase current induced in it would tend to decrease the starting torque. This effect, however, is small. The detail connections of the direct-current side of the converter are shown in Fig. 16.

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68. Reversed polarity with alternating-current self-starting converters. In this method of starting with a self-excited field winding, there is no method of predetermining the polarity of the direct-current terminals. However, if the converter falls into step with the wrong polarity, the machine may be forced to "slip a pole" (if the armature is connected to the low-voltage taps) by reversing the field switch. When the voltmeter indicates that the voltage is reversed, the field switch should be brought back to its original

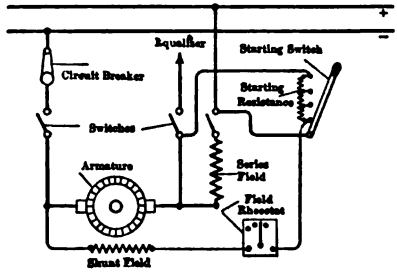


FIG. 17.—Direct-current self-starting connections.

position. In some converters, the field set up by the alternating-current may be so strong even at the lowest starting voltage that the converter cannot be made to "slip a pole" by reversing the field. Under these circumstances it is necessary momentarily to open and close the starting switch, repeating this operation until the correct polarity is obtained.

69. Direct-current self-starting. The converter may be started as a direct-current shunt-wound motor. The current flow at starting is limited by an adjustable resistance controlled by a multi-point starting switch. The connections for this method are shown in Fig. 17. If the transformers are solidly connected to the converter the starting current will be approximately doubled.*

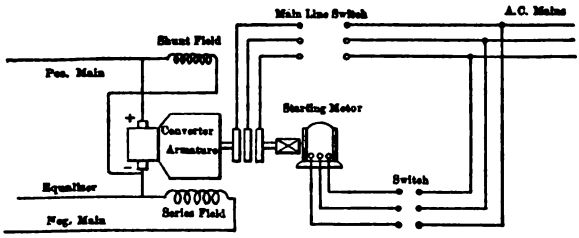


FIG. 18.—Alternating-current motor-starting connections with manual synchronising.

70. Alternating-current motor starting. A motor usually of the induction type is mounted on the converter shaft. The motor has fewer poles than the converter and, therefore, a higher synchronous speed. In starting, the motor is usually connected directly across the line. The connections for this method are shown in Fig. 18.

A modification of this method has recently been brought out by Dr. Rosenberg of Manchester, England, and by James Burke† in this country, which consists in connecting the starting-motor windings in series with the converter armature. This limits the starting current to a low value, and the

* Newbury, F. D. and Smith, M. W. "Starting Rotary Converte *Elect. Journal*, Jan., 1918.

† See U. S. Patent 1073662.

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alternating current in the converter armature causes it to lock automatically in synchronism.*

An older modification of the simple motor-starting method, designed to eliminate the necessity for synchronising, is the addition of reactance in the main circuit as shown in Fig. 19. When the starting motor has brought the converter armature near synchronous speed, the main-line switches are closed with the reactance in circuit. The resulting current in the converter armature causes it to lock in synchronism, after which the reactances should be short-circuited.

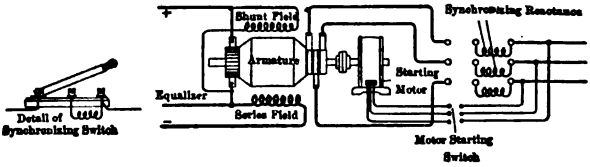


FIG. 19.—Alternating-current motor-starting connections self-synchronising with reactance.

71. Starting small single-phase converters. A method of starting, adapted to small single-phase converters, has been developed by the Wagner Electric Manufacturing Company, and is used on the small single-phase converters built by that company for charging electrical vehicle batteries, the supply of direct current for moving-picture arc lamps and similar purposes. A special distributed field winding is provided on the stator, so connected that with the double-throw starting switch in the starting position the converter starts as an alternating-current series-wound commutator motor. When the starting switch is thrown to the running position, the alternating-current leads are transferred to the collector-rings, the main-field winding is connected in shunt with the main direct-current armature leads and a part of the field winding is short-circuited to act as a damper winding. See Sec. 17, "Garage Equipment."

72. Methods of synchronizing. With the simple motor-starting method, or with the direct-current self-starting method, the converter must be synchronized with the alternating-current supply circuit before the main-line switches can be closed. The theory and methods involved are the same as employed in synchronising two alternating-current generators (Sec 7). Lamps or specially designed instruments (Sec. 3) may be used for indicating synchronism, as with generators.

With the motor method of starting, the running speed of the starting motor should, in general, be higher than the synchronous speed of the converter. The speed may be brought down to synchronous speed by increasing the load on the converter. This can be accomplished by increasing the voltage, thereby increasing the converter losses, or by connecting a resistance across the alternating-current terminals of the converter. Small adjustments in speed may be made by alternately opening and closing the starting-motor switch.

With the direct-current self-starting method, the speed regulation for synchronising is obtained by varying the converter shunt-field current. The series-field circuit is opened to insure more constant speed under the condition of varying armature current. To prevent a rush of current at the instant of synchronising, it is usual to leave a small amount of resistance always in the starting-rheostat circuit.

73. Comparison of different starting methods. The alternating-current self-starting method is used in most cases on account of its simplicity and its automatic synchronising feature. Its principal defects are the uncertainty in polarity and the large starting current required. In most cases wrong polarity can be corrected by means of the reversing field switch (Par. 66), and the amount of starting current is of importance (aside from the momentary line drop) only when the converter rating approaches the rat-

* Report of Com. on "Electrical Apparatus," National Electric Light Asso. Proceedings, 1914.

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ing of the alternator supplying it. With commutating-pole synchronous converters, the simplicity of this method is decreased by the necessity of lifting the direct-current brushes. The presence of the steel of the commutating poles greatly increases the armature flux during starting, which causes destructive sparking at the direct-current brushes. To avoid this objectionable feature, commutating-pole converters are provided with a special device for lifting all but two of the brushes (which indicate polarity) during the starting period.

The advantage of the alternating-current motor method of starting is the small current required and the certainty of obtaining correct polarity; the principal disadvantage is the necessity for synchronising. This disadvantage is overcome by the Rosenberg method or by the use of separate reactance coils (Par. 75). As compared with the alternating-current self-starting method, this method is somewhat more complicated and the necessary apparatus is more expensive. In some cases, however, where small values of starting current are imperative, it is the only method which will meet the requirements.

The direct-current self-starting method can only be used where direct current in sufficient amount is always available. It is very often used in large city lighting and railway substations. It has the advantage of minimum starting current and the absence of disturbances on the alternating-current supply system (which is particularly important on underground distribution systems). As with the simple alternating-current motor method, it has the disadvantage of necessitating manual synchronizing. This disadvantage has been overcome in some cases by combining the direct-current and the alternating-current self-starting methods. The converter is started by means of direct current, and when a speed near synchronous speed has been reached, the alternating-current switches are closed.

74. Parallel operation. When two or more converters are connected to the same low-tension bus on the alternating-current side and to the same bus on the direct-current side, the total direct-current load will divide among the several converters in the inverse ratio of the counter e.m.fs. of the converters and the resistances of the circuits. If two or more converters are so connected, the alternating-current and the direct-current bus bars close the circuit through any pair of converters; hence if the counter e.m.fs. of the two converters vary even slightly, considerable current will circulate between them. The counter e.m.fs. of different converters are seldom exactly the same, and the resistances, made up mainly of the direct-current brushes and brush contacts, are extremely variable—even in the same converter at different times. For these reasons it is not considered good practice to operate converters in parallel on both the alternating-current and the direct-current sides. Separate banks of transformers are usually provided—one for each converter. These not only open the circuit between converters, but also provide means for correcting slight differences in the voltage ratio of different converters.*

75. Division of load on the direct-current side is controlled by the same factors as in direct-current generators, and in addition by factors peculiar to the synchronous converter. Division of load is controlled by the voltage, so that all factors affecting voltage affect parallel operation. Parallel operation of shunt-wound converters, with or without auxiliary means for controlling the voltage, is as simple as parallel operation of shunt-wound direct-current generators. With compound-wound converters, equalizer leads are necessary as in direct-current generators. (Sec. 8.)

76. Corrections for improper division of load. With two converters operating in parallel on the direct-current side, one of which takes less than its proportionate share of the load, the load may be equalized by one or a combination of the following adjustments:

(a) **Adjustment of the series-shunt resistance.** The shunts on the series-field windings can be adjusted, decreasing the resistance of the shunt, if possible, on the overloaded converter or increasing the shunt, on the underloaded converter. It should be borne in mind, however, that changing the ampere-turns in the series field by changing the shunt resistance also changes the resistance of the complete series-field circuit. This change in shunt resistance must be compensated for by a corresponding change in the resistance of another part of the series-field circuit, so that the resistance of

* Newbury, F. D. "Parallel Operation," *Elec. Journal*, July, 1917.

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the total circuit remains unchanged. From another standpoint, a shunt on one converter series field may be considered to be a shunt on both series fields, the effect varying only by reason of the fact that the resistance of the leads and busses is added to one shunt circuit and not to the other (Sec. 8).

(b) **Insertion of resistance in leads between series-field and equalizer bus.** If the relative ampere-turns are correct but the series-field resistances are differently proportioned, the resistance of the leads between the series field and the equalizer bus may be changed to compensate for a difference in the series-field resistances. The resistance in the series circuit of the converter taking more than its share of the load should be increased. This adjustment varies the resistance of one series field without introducing a third parallel circuit between the equalizer and the main bus. Adjustment by this method is less complicated than an adjustment of the series-shunt resistance.

(c) **The transformer ratio can be changed.** This increases the voltage by the same amount throughout the range of load, and will not correct for an unequal division which changes with the total load. An increase in no-load voltage of one converter will cause, at lighter loads, a greater increase in proportionate load on that converter.

(d) **The reactance can be increased in the circuit of the lightly loaded converter,** which will raise its direct-current voltage and cause it to carry more nearly its proper share of the load. This method is similar in effect to an increase in the number of series-field turns, but the effect is obtained at the expense of a greater range in power-factor. It sometimes happens that the reactances of converters in parallel are worked at different saturations, with the result that the reactance voltages of the two converter circuits will have different ratios at light and at heavy loads. Such a relation will cause the converter with the more highly saturated reactance to take less than its share of the load at heavy loads.

(e) **The relative shunt-field currents of the two converters can be changed.** The converter having the smaller ratio of series-field ampere-turns to armature ampere-turns should have its shunt-field current increased. This will increase its no-load voltage (on account of change in power-factor) and cause it to take a greater share of the load at light loads. The voltages will tend to equalize as the load increases, a correct division being obtained at only one value of the load.

77. Load-division study. Since there are so many variables affecting load division, it is important to make a careful and systematic study of the particular case before making any changes. Such a study should be conducted as follows:

(a) Adjust the transformer ratios so that at no-load and with the shunt field adjusted to give equal power-factors, all converters have the same no-load direct-current voltage.

(b) The series fields should be adjusted by shunts so that the ratio of series-field ampere-turns to armature ampere-turns is the same.

(c) The resistances of the series fields (including shunt) plus the resistances of the leads from the series fields to the main bus (positive or negative) should be so adjusted that the resistances are inversely proportional to the rated capacities of the converters.

(d) The reactances should be adjusted, if possible, so that the reactance volts of the various circuits throughout the range of load are equal. If they cannot be made equal, the series ampere-turns should be greater in the converter having the smaller reactance, to afford an approximate compensation.

It is only possible to obtain correct division of load and equal power-factor on all converters when the machines are properly proportioned with respect to all four elements, namely: the transformer ratio, the series-field ampere-turns, the series-field resistance and the reactance.

78. Interruption of alternating-current supply by circuit breaker in substation. Under such conditions, if the converter is connected to another source of direct current, the converter will "motor" unless the direct-current breaker is opened by interlock with the alternating-current breaker (Par. **53**) or by a reverse-current relay. A compound-wound converter will run in the same direction when the direct-current power is reversed, the

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current in the series winding will be reversed (unless there are several converters in the same station connected to an equalizer bus), and the current in the shunt winding will remain the same in direction. With a single converter in a substation which is connected to other converters in other substations on the direct-current side, the converter will increase its speed due to the reversed series field. It may also increase its speed if the shunt field is adjusted for less than 100 per cent. power-factor. The increase in speed from the reversed series field will not be serious unless there is a circuit connected to the alternating-current side which will provide a load. Under these conditions the overspeed device will operate, thereby opening the direct-current breaker.

79. Interruption of alternating-current supply outside substation. In this case an interlock between the substation alternating-current and direct-current breakers will not operate to open the direct-current breaker, and reverse current or overspeed must be depended upon to protect the converter. In case of interruption of alternating-current supply the converter should be manually disconnected from the direct-current lines (if this is not done automatically) and the switches on the alternating-current side opened for starting.

80. Commutating-pole converters require more complete protection from low alternating voltage because of the excessive sparking at the commutator which is encountered when the converter is not in phase with the supply circuit. If the alternating voltage is lowered momentarily by a short-circuit or other cause, the converter may fall out of synchronism. When the voltage is restored the converter will not be in phase and the sparking may be sufficient to make the converter "buck." The conditions are similar to those which exist when starting the converter with the brushes down.

81. Protection of high-voltage converters. High-voltage converters (1,200 volts and above) should be more completely protected from abnormal conditions than low-voltage converters on account of the more destructive nature of the "bucking" when once started.

82. Sparking at the brushes may be due to any of the following causes: (a) brushes incorrectly set with reference to the neutral point. Correct setting is of particular importance in commutating-pole converters; (b) brushes of improper characteristics; (c) defective electrical design; (d) hunting; (e) severe overloads or extreme variation in load; (f) in non-commutating pole converters, low alternating voltage with large direct-current loads; (g) brush holders insufficiently supported; (h) brushes stuck in holders or inaccurately fitted to commutator; (i) improper brush tension; (j) rough commutator due to high bars, to high mica or to flat spots.

83. Bucking or flashing may be brought about by any condition causing excessive voltage in the coils short-circuited by the brush or between adjacent commutator bars, or may be caused by abnormally low-surface resistance on the commutator between adjacent brush arms. Any condition tending to produce poor commutation increases the likelihood of bucking. Excessive voltage under the brush is usually caused by short-circuits of varying degree. Most direct-current machines will flash if short-circuited at the terminals and the direct-current voltage is maintained. Short-circuits in service usually occur on the line, so that some resistance exists between the "short" and the machine, thereby limiting the current. Taps from feeders to trolley should always be located some distance from the substation.* Excessive voltage between commutator bars is caused directly by increased line voltage, or is indirectly caused by extreme current overloads which distort the field flux. Increased line voltage may be due to disturbances on the high-tension distributing system induced by lightning, switching, short-circuits, etc. A decrease in the insulation strength between brush arms may be due to the presence of conducting gases formed by a relatively small flash or of foreign substance such as dirt or water. Most flashing is caused by the formation of conducting gases. Ordinary types of circuit breakers do not act quickly enough to protect machines from abnormal changes in

*Smith, C. H. "Relation of Trolley Feeder Taps to Machine Flashovers," *Elec. Journal*, Jan., 1915.

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current or voltage. On short circuits, for example, the current increases far beyond the setting of the breakers before the circuit is finally opened.

84. Reactance used as a protection against short circuits. Shunt-wound synchronous converters may be protected from the effects of short circuits by inserting reactance in the alternating-current leads.

TESTING

85. The tests ordinarily made on synchronous converters are as follows: (a) resistance measurements; (b) polarity determination; (c) ratio of voltages; (d) core-loss and saturation test; (e) alternating-current short circuit or synchronous-impedance test; (f) starting tests; (g) voltage regulation test; (h) temperature tests; (i) commutating-pole saturation test.

86. Measurement of resistance. Resistances may be measured either by the bridge method or by the use of ammeter and voltmeter as in direct-current machines. It is customary in obtaining the armature resistance to measure the resistance both on the direct-current side between the proper commutator bars, and on the alternating-current side between the corresponding slip-rings.

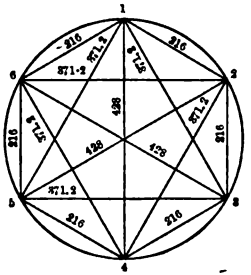


FIG. 20.—Diagram of converter voltages between collecter-rings.

87. Determination of polarity. The correct polarity of the field windings is determined in the same manner as for direct-current generators. The relative polarity of the shunt and the series windings in the compound-wound converter is also determined the first time the converter is under load.

88. Determination of voltage ratio. In order to determine whether the various taps from the armature winding have been brought out correctly and connected to the proper rings, readings of voltages between each ring and every other ring are taken. During the test the direct-current voltage is held constant at some convenient value. The armature winding is usually connected to the collector-rings so that adjacent rings have the minimum voltage possible between them. Under these conditions the voltage between adjacent rings is given by the following formula, N being the number of rings:

$$E_{ac} = \frac{E_{dc}}{1.415} \left(\sin \frac{180 \text{ deg.}}{N}\right) \quad \text{(volts)} \qquad (3)$$

A convenient method of checking the values obtained on test is to construct a diagram such as that in Fig. 20. The numbers outside of the circle represent the collector-rings. The voltages shown were actually obtained from a 600-volt six-ring converter.

89. Determination of core-loss, saturation, friction and windage losses. This test is made either by driving the converter by a small direct-current motor or by driving the converter itself as a direct-current shunt-wound motor. The test is the same as the corresponding test of a direct-current generator except that alternating voltages are obtained as well as the direct-current voltage, in order to obtain the actual voltage ratio. If the converter is self-excited during the test, the measured loss must be decreased by the field-winding and rheostat losses. The **brush friction** is determined by the difference in the measured losses with the brushes down and the brushes up. This reading is of no value unless the commutator has a good polish and the brushes are well seated. The **friction and windage losses** are determined by the difference in measured converter losses with the brushes removed, and with the driving motor running disconnected from the machine under test.

90. Starting tests. With the alternating-current self-starting method, a test is made to check the sufficiency of the starting voltage to bring the converter up to synchronous speed. It is customary to measure the voltage, current and time required to reach synchronous speed. With the induction-motor method of starting, the test is made to ascertain whether the load on the starting motor (provided by the converter) is such as to permit it to

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operate sufficiently near the converter synchronous speed at the normal converter voltage, so that synchronizing will be possible. If the normal losses of the converter are not sufficient to reduce the starting-motor speed to the converter synchronous speed, it is necessary to determine the additional load required.

91. The voltage-regulation test can be made only when the entire equipment of transformers and reactances to be installed with the converter is available. Even under such circumstances the test must be made on the basis of constant alternating voltage on the high-tension side of the transformers. This is rarely, if ever, true in practice, so that the test unless made after installation is of little value and is seldom made. Furthermore, there is no object in adjusting the series winding of a converter except in conjunction with all other converters with which it is to operate in parallel on the direct-current side. With compound-wound converters, the alternating voltage should be adjusted to the desired value, and the shunt field of the converter should be adjusted to give the correct voltage at no load. If the transformer ratio is correct, this will require considerable lagging current, which may be obtained by under-excitation. Load is then placed on the converter and the desired full-load voltage is obtained by adjusting the series-field shunt. This test is never made with shunt-wound converters since a slightly drooping voltage characteristic would always be obtained, and there is no means within the converter of modifying it. With converters designed for wide voltage ranges, it is customary to observe the operation at the maximum and minimum pressures to insure that there is sufficient range in the field windings and rheostats to obtain 100 per cent. power-factor at all voltages, and that satisfactory commutation is obtained throughout the voltage range.

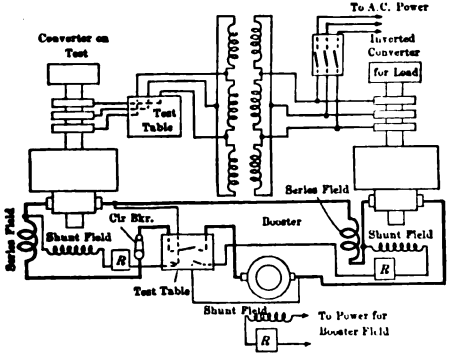


FIG. 21.—Loading-back temperature-test connections.

92. The temperature tests at the factory are performed either by direct loading on resistances or by "**loading back**" on a similar converter or power circuit. In the loading back method (using a similar converter), the losses can be supplied from either the direct-current or alternating-current sides as is found convenient. The alternating-current sides of the machine under test and of the test machine may be connected together by a complete metallic circuit, or through transformers having a one-to-one ratio. The latter arrangement is preferable, as conditions are thus made more stable and can be more easily controlled. The connections for such a test are shown in Fig. 21. When the machines under test are compound-wound, it is necessary to reverse the series field of the converter running inverted. In Fig. 21 the losses are supplied partly from the alternating-current side and partly by a booster in the direct-current side. Temperature tests are usually made with 100 per cent. power-factor at the converter collector-rings. To obtain this

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condition, the shunt field should be adjusted for the proper no-load voltage, and the series field shunted to give 100 per cent. power-factor, that is, a minimum value of armature current, at the tested load.

93. **Commutating-pole saturation test.** On commutating-pole converters this test is made to determine the sensitiveness of the converter to proper adjustment of the commutating-pole ampere-turns. The converter is so connected that it can be loaded with the commutating poles separately excited, in order that the excitation can be adjusted. For various loads and, in variable voltage converters, for various voltages, the minimum and the maximum commutating-pole excitations are determined between which satisfactory commutation is obtained.

94. **Determination of efficiency.** Efficiencies are usually determined by separate measurements of the various losses. This method does not derive the true efficiency, as the so-called load losses or stray losses cannot be included by direct measurement. This is the conventional efficiency defined in Sections 3524 and 4335 A. I. E. E. Standardization Rules, 1921 Edition. Stray losses, however, in converters are small and no appreciable error is introduced by omitting them. They are less in low-frequency converters than in high-frequency converters. On account of the relatively small losses involved and the large number of instruments to be read, input-output efficiency tests can be made satisfactorily only under laboratory conditions where the power input and output are absolutely steady, and where carefully calibrated instruments are read by skilled observers. Unless the test can be made under such conditions more accurate results will be obtained by calculating the efficiency from the separate measurable losses, and including a reasonable allowance for the stray losses.*

The reason for the greater accuracy of the efficiency calculated from the separate losses is apparent when it is remembered that a 2 per cent. error in the measurement of the losses results in only 2 per cent. of the 5 per cent losses (using 95 per cent. as the true efficiency) or 0.1 per cent. error in the efficiency, while 2 per cent. error in the input-output test affects the efficiency by an equal percentage.†

INVERTED CONVERTERS

BY F. D. NEWBURY, M.E.

95. **Any synchronous converter can be operated inverted;** that is, it can be used to convert direct current into alternating current.

96. **The internal action of the inverted converter** is the same as that of the synchronous converter except that the losses are supplied from the direct-current side, so that the distribution of currents in the armature is slightly different.

97. **The inverted converter has the speed characteristics of a direct-current motor** instead of a synchronous motor, except that when the converter operates in parallel with another source of alternating current the speed is controlled by each of the two alternating-current sources in proportion to its share of the load. When an inverted converter operates singly, its speed may be seriously affected by a change in load or power-factor on the alternating-current side. A lagging alternating-current load will demagnetize the main fields and the converter speed will increase, as would that of any direct-current motor with weakened field.

98. **Alternating voltage control.** There is no means of varying the alternating voltage corresponding to the reactance and series-winding method used with the synchronous converter. The alternating voltage may be controlled by any of the other methods discussed in connection with the synchronous converter.

99. **Inverted converters are usually shunt-wound** in order to secure as nearly constant speed and frequency as possible.

100. **Correction for overspeeding.** Where inverted converters are subject to loads of varying power-factor and where constant speed is essential, it is customary to use a separately excited field winding, the excitation being

* Olin and Henderson. "Load Loss Correcting Factors," *Transactions* A. I. E. E., page 479, Vol. XXXII, Part I. Robinson, L. T. "Determination of Stray Losses from Input-output Tests," *Transactions* A. I. E. E., page 531, Vol. XXXII, Part I.

† See footnote, Par. 22.

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supplied by a direct-connected exciter. The exciter is designed with an unsaturated magnetic circuit so that a change in speed will produce a maximum change in exciter voltage. With this arrangement an increase in speed of the inverted converter is at least partially corrected by the increase of its excitation due to increased exciter voltage.

101. Protection against overspeeding. Where the conditions do not require the separate exciter, it is customary to install an overspeed tripping device to protect the converter and its alternating-current load from excessive speed due to unusual conditions.

102. Applications of the inverted converter. The following applications of the inverted converter may be mentioned: (a) to supply a small amount of alternating-current from an existing direct-current supply; (b) to form a connecting link between alternating-current and direct-current systems for the transfer of energy in either direction. Under the latter condition the converter may operate either direct or inverted. An induction regulator or other means of varying the voltage is necessary to control the transfer of energy through the converter or, in the case of operating the load on one system entirely through the converter, to compensate for the voltage drop in the converter and transformers. (c) To enable a storage battery to be used to equalize the energy input in an alternating-current system. Here, also, a means of varying the voltage of the converter is necessary to control the charge and discharge of the battery. A notable installation of this kind is at the Indiana Steel Company, where a 2,000-kw. 250-volt, 25-cycle split-pole converter is used.

MOTOR CONVERTERS

BY F. D. NEWBURY, M.E.

103. Structure. The motor converter, or cascade converter, as it is sometimes called, consists of two elements, or machines, coupled together mechanically and electrically. The primary element, having the structure of an induction motor with a phase-wound rotor, performs the functions of a voltage, frequency and phase converter and of an induction motor. The secondary element, having the structure of a synchronous converter (with taps to the winding but without collector rings), performs the functions of a direct-current generator (driven by the induction motor, the rotors being mounted on the same shaft) and of a synchronous converter (receiving energy of suitable voltage, frequency and phase from the rotor winding of the primary element).*

104. Starting resistance. Three of the inside terminals of the rotor winding of the primary element are attached to collector-rings, to which the starting resistance is also connected. When operating at synchronous speed, all of the inside terminals of the rotor winding of the primary element are connected together to form the neutral.

105. The rotor of the primary element is wound with either 9 or 12 phases, the large number of phases being used to decrease the armature copper loss of the commutating machine. The large number of connections between the two rotors does not lead to any complication as they can be made solidly without collector-rings.

106. Transformers are required only when the line voltage exceeds the highest voltage for which the primary element can be safely and economically wound. In this respect the motor converter is on nearly equal footing with the synchronous motor-generator set. The difference in favor of the latter is due to the fact that the synchronous motor can be satisfactorily wound for higher voltages than the induction-motor element of the motor converter.

107. Applications. The motor converter occupies a position between the motor-generator set and the synchronous converter. Its main advantage over the motor-generator set lies in the fact that a part of the energy is transformed electrically and, therefore, more efficiently than in the motor-gener-

* (a) See German patent 145434 (1902); English patents, 3704 (1903), 7807 (1904); U. S. patent 72400 (1904).
(b) See Arnold u. la Cour, "Der Kaskadenumformer" Enke, Stuttgart, 1904.
(c) Hallo, H. S. "The Theory and Application of Motor Converters," *Journal*, I. E. E. (London), Vol. XLIII, page 197.

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ator set in which all of the energy is transformed mechanically. For the same reason it is less efficient than the synchronous converter in which the entire output is transformed electrically. Its main advantage over the synchronous converter lies in the fact that the commutating machine of the motor converter operates at a frequency lower than the line frequency—usually at half the line frequency. This advantage applies only in the case of line frequencies above 40 cycles per sec. and for the higher direct-current voltages, and has been lessened even for these conditions by recent improvements in high-frequency synchronous converters. The motor converter has found its most extensive application in England and Germany. In England approximately 150,000 kw. of capacity has been installed since 1904, and in Germany approximately 65,000 kw. of capacity has been installed, mainly since 1908. These figures were compiled in July, 1913. Practically nothing has been done in the United States toward introducing the motor converter commercially, mainly due to the previous development of the high frequency synchronous converter.

108. Equations of the motor converter.

$$\text{Synchronous speed} = \frac{\text{Line frequency} \times 120}{\text{Sum of poles of both elements}} \quad \text{(r.p.m.)} \quad (4)$$

$$\text{Rotor frequency} = \text{Line frequency} - \left(\frac{\text{Primary poles}}{120}\right) \text{(r.p.m.)}$$

$$\text{(cycles per sec.)} \quad (5)$$

$$\text{Power transformed electrically} = \text{Total output} \left(\frac{\text{Secondary poles}}{\text{Total poles}}\right) \quad (6)$$

$$\text{Power transformed mechanically} = \text{Total output} \left(\frac{\text{Primary poles}}{\text{Total poles}}\right) \quad (7)$$

When the numbers of poles of both elements are equal, as is usually the case, these relations obviously become very simple.

109. The average armature current and heating in the commutating element is less than in a direct-current generator of equal rating, but more than in the corresponding synchronous converter. Assuming an equal number of poles in the two elements of a motor converter, the commutating element is operating half as a direct-current generator and half as a synchronous converter. Assuming further a twelve-phase rotor circuit and 100 per cent. power-factor at the terminals of the primary element, the average loss will be approximately 0.34 (relatively), the equivalent direct-current generator loss being unity. This is about 30 per cent. greater than the average loss in the ordinary six-phase synchronous converter, also at 100 per cent. power-factor. The maximum loss in one conductor is approximately 10 per cent. less than the maximum loss in the six-phase synchronous converter, at 100 per cent. power-factor.

110. The armature loss increases less rapidly with reduction in power-factor than in the 6-phase synchronous converter, due to the generator current loss, which does not vary with power-factor, and to the higher number of phases employed.

111. Power-factor. The power-factor at the line terminals of the primary element may be varied as in the simple synchronous converter by varying the field excitation of the commutating machine. The magnetizing current for the primary element may be taken from the line or from the secondary element as desired. This is controlled by the excitation of the commutating machine. If the set is operated at 100 per cent. power-factor, it follows that the secondary element is operating at a leading power-factor (with respect to line voltage) in the neighborhood of 93 per cent. at full-load. This has an important bearing on the heating and size of the commutating machine. See Par. 117.

112. Voltage control. A fixed voltage ratio exists between the alternating-current, and the direct-current sides of the commutating element of the motor converter, as in the synchronous converter, and the same means for varying the direct-current voltage must be employed. In a shunt-wound motor converter the direct-current voltage drops with the load assuming constant alternating voltage. In this case the necessarily high reactance of the primary element is a disadvantage. In a certain 500-kw.

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motor converter the voltage dropped 5 per cent. between no load and full load. This is less than in a corresponding direct-current generator but more than in a corresponding synchronous converter. The motor converter is well adapted to voltage regulation by reactance and series-field excitation. In general, the primary element will contain inherently sufficient reactance to obtain a 10 per cent. voltage increase (assuming constant primary alternating voltage) with permissible range in power-factor. This range in voltage is ample for the ordinary railway system. Voltage ranges of 20 per cent. to 30 per cent. required by lighting systems using storage batteries cannot be obtained economically by reactance and series-field excitation. For such voltage variation an induction regulator, alternating-current booster or direct-current booster is required. The alternating-current synchronous booster must have the same number of poles as the secondary element and must be connected, electrically, between the primary and secondary rotor windings.

113. **Relative size and cost.** The cost of the primary or induction element will be approximately the same as that of an induction motor with phase-wound rotor at double the running speed (assuming equal primary and secondary poles). The cost of the secondary or commutating element will be less than that of a direct-current generator of the same rating and more than that of a synchronous converter of the same rating and operating frequency. The cost of the induction element will be somewhat more than that of stationary transformers necessarily used with the synchronous converter. On the basis of a line voltage so low that transformers are unnecessary with the motor converter, the cost without transformers is approximately the same as that of the higher-frequency synchronous converter and the necessary transformers. In case transformers must be used with either form of converter on account of high line voltage, the cost of the motor converter installation will be from 30 per cent. to 40 per cent. greater than the synchronous converter installation.

114. **Efficiency.** At capacities of 500 kw. and above, the efficiency of a synchronous converter and transformers would be 1.5 per cent. to 2 per cent. better than the motor converter without transformers, assuming American conditions which require the use of open armature slots in the primary element. Including the transformer in the motor converter installation would reduce its efficiency below that of the equivalent synchronous converter installation from 3 per cent. to 4 per cent.

115. **The method of starting** is the same as in an induction motor with phase-wound rotor, a three-phase resistance controller being used as indicated in the diagram in Fig. 22. It will be noted that, during starting, three phases of the rotor winding of the induction element are in series with the armature winding of the commutating element, the other phases remaining open at the neutral. After the main-line switch is closed, the rotor circuit of the induction element is closed through the starting resistance. As the rotor begins to revolve, two alternating currents are superimposed in the rotor circuits, one at maximum frequency decreasing with the speed, due to the induction element, and one at minimum frequency increasing with the speed, due to the commutating element. The latter current is appreciable only near synchronism or in the case of separate direct-current excitation of the secondary element. As the rotor approaches its normal running speed, these two currents approach the same frequency, which is indicated by a slow oscillation of the needle of the voltmeter connected in the starting circuit. At the moment the voltmeter needle passes through zero, the starting resistance is short-circuited and the set will thereafter operate synchronously. The neutral points of all the rotor phases are connected together and the starting brushes lifted from the rings by a mechanical device. By proper selection of the starting resistance, the starting current may be maintained at a low value throughout the entire starting operation. Due to the small armature current during starting, the direct-current voltage will always build up with the correct polarity. The field reversing switch commonly used with alternating-current self-starting synchronous converters is unnecessary.

116. **The motor converter may be used to supply a three-wire direct-current circuit** without change except that the brushes are left on the rings after starting. They are connected to the middle terminals of a

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three-pole double-throw switch, one set of outside terminals being connected to the starting resistance and the other set being short-circuited and connected to the direct-current neutral lead.

117. Commutating poles may be used on the commutating element as in any synchronous converter. Due to the combined generator and converter action the ampere-turns required on the commutating poles more nearly approach the ampere-turns on the equivalent direct-current generator than on the equivalent synchronous converter.

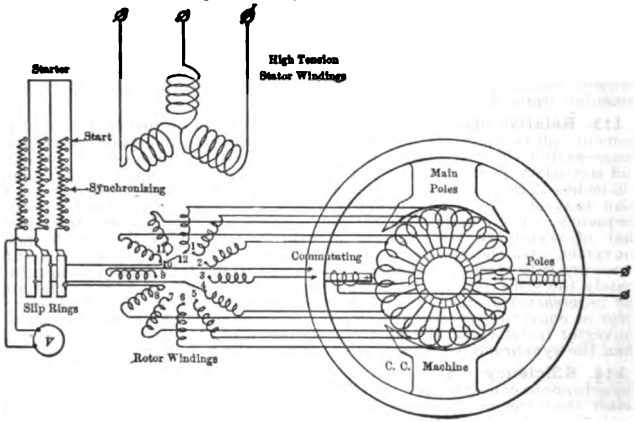


FIG. 22.—Diagram of connections of motor converter.

DIRECT-CURRENT CONVERTERS

BY ALEXANDER GRAY, M. S.

118. Theory of operation. A three-wire generator, operating with no current in one side of the system, may be used as a direct-current converter with a ratio of two to one. Such conditions of operation are shown diagrammatically in Fig. 23. If the armature be connected across the terminals a and b, it will rotate as a direct-current motor armature and will take a current i, at a voltage $2e$, to supply the no-load losses in the machine. If now two diametrically opposite points c and d be connected through a coil C of high reactance and negligible resistance, and if the middle point f of the coil be connected as shown in Fig. 23, the machine will become a three-wire generator (Sec. 8, Par. 193). The point f is then midway in potential between c and d and, since the e.m.f. between c and d is alternating, an alternating current, supplied from the mains, will flow in the reactance coil. This current will be small since the reactance is large.

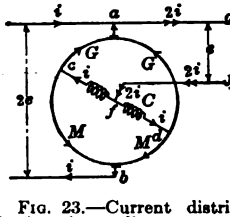


FIG. 23.—Current distribution in a direct-current converter.

A load current at voltage e may now be drawn from terminals f and g, and the current distribution in the system will then be as shown in Fig. 23, the no-load currents being neglected. The currents in sections M flow against the generated e.m.f., so that these sections may be considered to act as motors; the currents in sections G flow in the direction of the generated e.m.f., and so these sections may be considered to act as generators. The driving torque due to the motor sections must overcome the retarding torque due to the generator sections.

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119. Armature currents. The current in the armature conductors varies as the armature revolves; this may be seen from Fig. 24 where the armature is shown in four different positions.

In position *A*, the resistance from *c* to *a* is equal to that from *c* to *b*, and the current *i*, entering the armature at *c*, divides into two equal parts. In position *B*, the resistance from *c* to *a* is less than that from *c* to *b*, and the current i_a is greater than the current i_b.

In position *C*, the current in *ca* is practically equal to *i* and that in *cb* practically zero. In position *D*, the currents in all the conductors are zero.

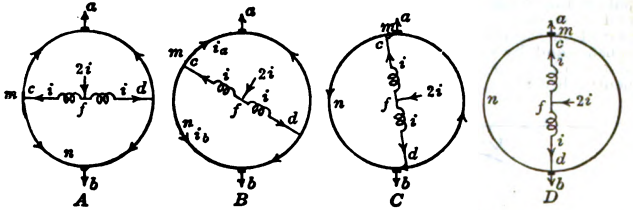


FIG. 24.—Relation between current and position of armature.

Fig. 25 shows approximately how the current varies in two coils *m* and *n* as the armature makes one revolution. In coil *m*, the current varies from zero to *i* while in coil *n* it varies from $-\frac{1}{3}i$ to $+\frac{1}{3}i$; the armature coils are therefore not equally heated. Those next the leads *c* and *d* are the hottest and those midway between the leads are the coolest.

120. The rating of a direct-current converter depends upon the number of phases of the reactance coil. With a 2-phase reactance coil, as shown in Fig. 26, the maximum current in the conductors is less than *i*, and the current in each armature coil is more nearly constant than when only one reactance coil is used. For the same average armature copper loss in each

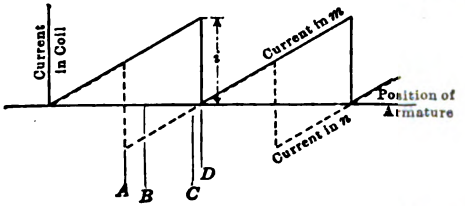


FIG. 25.—Variation of current in coils *m* and *n* during one revolution of armature.

case, a direct-current generator can be given the following ratings when used as a direct-current converter:*

1.00 as a direct-current generator;
1.22 as a direct-current converter with one reactance coil;
1.55 as a direct-current converter with two reactance coils;
1.64 as a direct-current converter with three reactance coils.

The cost and weight of the equivalent direct-current generator may be obtained from Fig. 67 (Par. **178**) Sec. 8, an addition of 5 per cent. being made for the slip-rings.

121. The secondary voltage of such a system cannot readily be controlled independently of that of the primary; it decreases with increase of load according to Eq. 38 in Sec 8, Par. **194** and, with a reasonably priced

* Steinmetz, C. P. "Elements of Electrical Engineering," p. 337.

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reactance coil, this decrease in voltage can hardly be less than 3 per cent. at full load.

122. The rating of the necessary reactance coil may be found from Sec. 8, Par. **197.** The frequency, which equals the number of poles multiplied by the r.p.m. and divided by 120 will generally be between 15 and 40 cycles per sec.

123. The Dettmar and Rothert split-pole machine (Sec. 8, Par. **122**) when used as a direct-current converter has the advantage that the secondary voltage can be controlled independently of that of the primary. Each pole of this machine is split so as to form two polar projections of like polarity and these are excited independently of one another. The neutral brush is placed on the commutator midway between the positive and the negative brushes and, by varying the excitation of one polar projection relative to that of the other, the flux entering the armature between the positive and the neutral brushes may be changed relative to that between the neutral and the

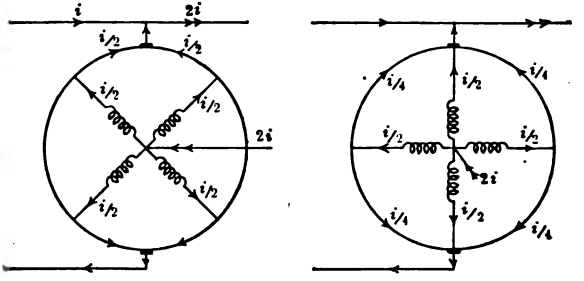


FIG 26.—Current distribution in a direct-current converter with a two-phase reactance coil.

negative brushes, or the potential of the neutral brush may be varied as desired. By the use of suitable shunt and series coils on the polar projections, any desired degree of compounding may be obtained and, in the extreme case, a constant current may be obtained from the secondary of such a machine while the primary is operating at constant potential.

124. The C. M. B. autoconverter is another type of split-pole machine with the armature tapped by brushes placed between the main positive and negative brushes. A standard line of these machines is on the market and can be supplied with a transformation ratio as high as four to one, and with such a combination of shunt-field and series-field coils that a drooping secondary characteristic may be obtained if desired for constant-current operation. They are supplied with ball bearings and have an efficiency which varies from 75 per cent. for a 1 kw. unit to 86 per cent. for a 10 kw. and 94 per cent. for a 50 kw. unit.

125. **Applications.*** Direct-current converters of this latter type are used in place of motor-generator sets for many purposes, among others, to obtain 50 volts from a line of higher voltage for the operation of arc lamps at 50 volts in bioscope sets and search lamps. A constant-current characteristic is the most suitable for arc-lamp operation. They are also used for electric welding, the machines being built with such characteristics that, on short-circuit, the current is only 10 per cent. more than full-load current, while the voltage drops practically to zero.

* For further information on direct-current converters see:
Steinmetz, C. P. "Theoretical Elements of Electrical Engineering," page 337; New York, McGraw-Hill Book Co., Inc.
MacFarlane and Burge. *London Electrician*, July 9, 1909.
Thompson, S. P. Report at Turin Congress; *London Electrician*, Sept. 29, 1911.

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DYNAMOTORS

BY ALEXANDER GRAY, M. S.

126. General description. The dynamotor is similar to the motor-generator set except that the two armature windings are on the same core and revolve in the same magnetic field, each winding being connected either to a commutator or to collector-rings, in accordance with its use for direct or for alternating current respectively. It is rarely necessary to change from direct current to alternating current, so that machines for such purpose are special. A change from alternating to direct current may be realized with less expense by the use of a rotary converter, with a transformer if necessary, than with a dynamotor.

127. Armature reaction. The armature for a direct current to direct-current type of dynamotor is shown diagrammatically in Fig. 27. Here the transformation ratio is four to one, so that there are four times as many effective turns in one winding as in the other. The direction of the generator current is that of the generated e.m.f., but the current in the motor winding is in the opposite direction. If the losses in the machine be neglected, then the

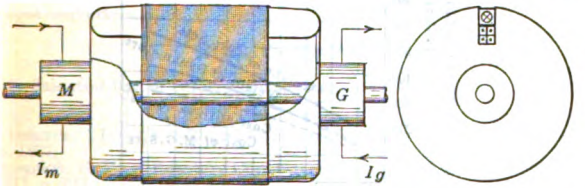


FIG. 27.—Arrangement of dynamotor armature and commutator.

motor input, $E_m I_m$ equals the generator output, $E_g I_g$, and the value of effective ampere-turns in the motor armature, $n_m I_m$ equals the value of effective ampere-turns in the generator armature, $n_g I_g$. Therefore the m.m.fs. of the two windings are equal and opposite and there is no resultant armature reaction. For this reason, the dynamotor can be allowed a smaller air gap, a smaller exciting current, and a lighter field coil than a standard machine built upon the same frame.

128. The commutation of these machines is exceedingly good if the brushes on the two commutators are so placed that the short-circuited coils of each of the two windings lie in the same slot. Under such conditions the currents in these coils change at the same time and in opposite directions, so that the reactance voltage is small (Sec. 8, Par. 43). Dynamotors can therefore have deep slots and low-resistance brushes and in consequence are suitable for delivering large currents at low voltages.*

129. Voltage regulation. The principal objection to the standard dynamotor is that the secondary voltage cannot be regulated without changing the excitation of the primary. The ratio of the terminal voltages is fixed by the ratio of effective armature turns and by the voltage drop due to the resistance of both armature windings, so that the terminal-voltage ratio is independent of the excitation and changes with the load. The transformation ratio for a given load can be changed only by inserting a resistance or a booster in the primary or the secondary circuit.

130. Combined dynamotor and booster. A machine which is equivalent to a combined dynamotor and booster can be made by extending one armature winding a longer distance axially along the core than the other, and applying to this extended part of the core a magnetic field from an auxiliary field system. The exciting current for this auxiliary field can be so regulated as to change the voltage of one winding independently of that of the other. If this field system be excited with series-field coils, the secondary voltage can be made to vary with the load, as desired. The chief advantage of this latter machine over the motor-generator set is that it requires less

* Sheldon and Hausmann. "Dynamo-electric Machinery," Vol. I, page 266.

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floor space and will have a higher efficiency, but will probably not be cheaper if the machines are of corresponding construction.

131. A special dynamotor is extensively used for telephone ringing. The motor winding is for direct current and the other winding is connected to two slip-rings in order to deliver alternating current at from 16 to 19 cycles per sec., and about 75 volts (effective).

132. Dynamotors can be used in place of motor-generator sets only when the regulation of voltage is not of great importance as, for example, in the ringing of bells and gongs, the operation of signals in connection with fire alarms, telephone systems, annunciators and many other kinds of signaling, and the operation of magnetic contactor switches. For telegraphic work, dynamotors are often used in place of primary batteries, the secondary voltage being 50 to 500 volts direct current, depending on the length of the line (Sec. 21).

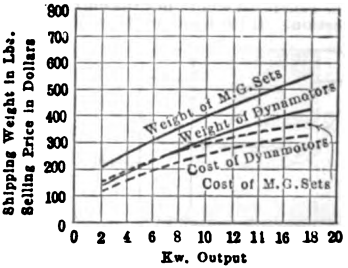


FIG. 28.—Weights and costs of small dynamotors and motor-generator sets.

133. Cost of Dynamotors. Since the two armature windings are upon the same core, that core will be larger for a dynamotor than for a generator of the same output. Fig. 28 shows the shipping weights and selling prices of small dynamotors and motor-generator sets of substantial make on a single bed plate, the motor-generator set consisting of two machines joined by a flexible coupling.

DOUBLE-CURRENT GENERATORS

BY F. D. NEWBURY, M.E.

134. Armature currents in the double-current generator. A machine having the same structure as the synchronous converter may be used to generate both alternating and direct current if driven by a suitable prime mover. Unlike the synchronous converter, the armature currents in the double-current generator are not less than in the corresponding direct-current generator. The alternating and direct-current are not subtractive as shown in Figs. 1 and 2, but are additive, since both are generator currents. For the same reason, the generation of both alternating and direct current in the same armature winding is not favorable to commutation as in the synchronous converter, but is detrimental.

135. Dependance of direct-current voltage on alternating voltage. A double-current generator has none of the advantages of the synchronous converter and has many disadvantages of its own. One of the most serious disadvantages is the dependence of the direct-current voltage on the alternating voltage and on variations in alternating-current load and power factor. A change in alternating-current load or power-factor will cause a change in the magnetizing effect of the alternating current in the armature winding and thus change the resultant magnetisation on which the direct and alternating voltages depend. To assist in maintaining steady direct-current voltage, it is customary to excite double-current generators separately.

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136. Alternating-current parallel operation. If double-current generators are operating in parallel with a relatively large alternating-current system on which the alternating voltage is held constant, the direct-current voltage will also be constant and cannot be varied independently of the constant alternating voltage.

137. Limitations of design. From the design standpoint, the double-current generator is handicapped by the rigid relationship between poles and speed required by the frequency. This, in general, results in the use of many more poles than would be employed in an equivalent direct-current generator, causing an appreciable increase in cost. This is particularly true with slow engine speeds and high frequency. It is also impossible to use commutating poles on account of the effect of variation in alternating-current load and power-factor. No machines larger than 2,500 kw. have ever been built in this type.

138. Abandonment of slow-speed type. During the past 10 years, no slow-speed engine-driven double-current generators of any importance have been installed. The reasons for this have been the disadvantages of the double-current generator already enumerated and the lower cost and greater flexibility of alternating-current generators used in conjunction with synchronous converters.

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SECTION 10

POWER PLANTS

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SECTION 10

STEAM POWER PLANTS

BY REGINALD J. S. PIGOTT

LAWS OF HEAT TRANSFER

1. No heat can be transmitted from a cold body to a hotter one: flue gases must, therefore, leave the boiler at not less than the steam temperature in an ordinary boiler, or at not less than the incoming feed-water temperature in the counter-current type of boiler.

2. Two kinds of heat transfer take place in a boiler; absorption by radiation from incandescent fuel direct to heating surface, and heat transmission by contact and convection. Stefan and Boltzmann's law states that absorption by radiation is proportional to difference of the fourth powers of the two temperatures involved.

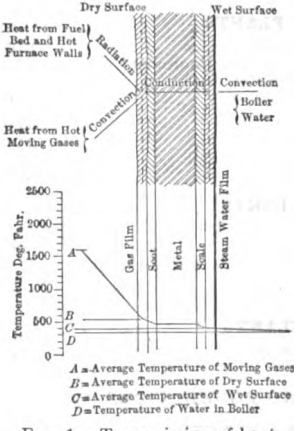


FIG. 1.—Transmission of heat.

B.t.u. radiated per sq. ft. per hour = $16 \times 10^{-10} (T_1^4 - T_2^4)$ (1)

where T_1 = absolute temp. in deg. Fahr. of "black" incandescent body, and T_2 = absolute temp. in deg. Fahr. of receiving body.

A "black" body such as carbon, in any form except the crystalline, will absorb all heat transmitted, reflecting none. Metal and other materials will reflect from one-fourth to one-half of that received.

3. Heating by convection from hot gases to water is proportional to some power of each of the velocities of the moving gases and water or steam. The heating is also proportional to the density of the fluids and to the absolute temperatures, since these influence the molecular energy. The formula for heat transfer by convection is,

$$H = A\,U(T_1 - T_2) \qquad (2)$$

where H = B.t.u. transmitted per hr., A = area, sq. ft., U = transmission coefficient, $T_1 - T_2$ = mean temp. diff.

4. The transmission coefficient for normal rating is somewhere around 5 to 8 B.t.u. deg. of mean temperature difference, per sq. ft., per hour, but may be much larger than this in boilers with much surface exposed to radiant heat and well scrubbed by the gases. The upper limit has probably never been reached, the maximum value for recorded tests being about 20.

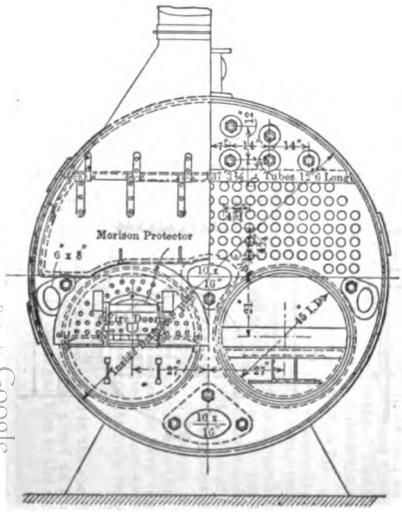
5. Effect of dirty surfaces. One important difference noticeable between absorption of heat by conduction and by radiation is that the relative cleanness of the surface affects the rate of conduction very readily, but absorption of heat by radiation is practically unaffected. Soot increases the thickness of the film of motionless gas, besides adding its own resistance to heat flow.

6. The resistance of the film of inert gas entangled in the rough surface of the tube (or soot) is from 20,000 to 35,000 times as great as that of the metal tube alone, so that the thickness of the dead gas film is the controlling

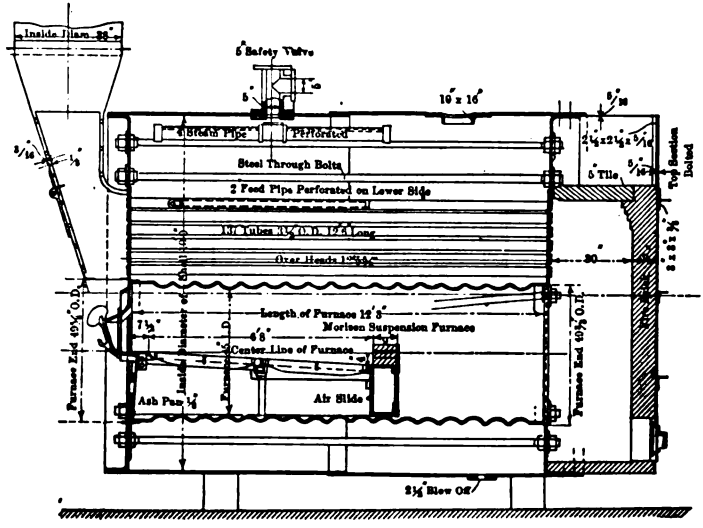
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FIG. 2.—Horisontal return tubular boiler.

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Front Exterior Elevation



Longitudinal Section Elevation

FIG. 3.—Scotch marine boiler.

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factor. In absorption of heat by radiation, however, the interposition of a gas film or layer of soot has practically no effect, since conduction does not bear a part in the action.

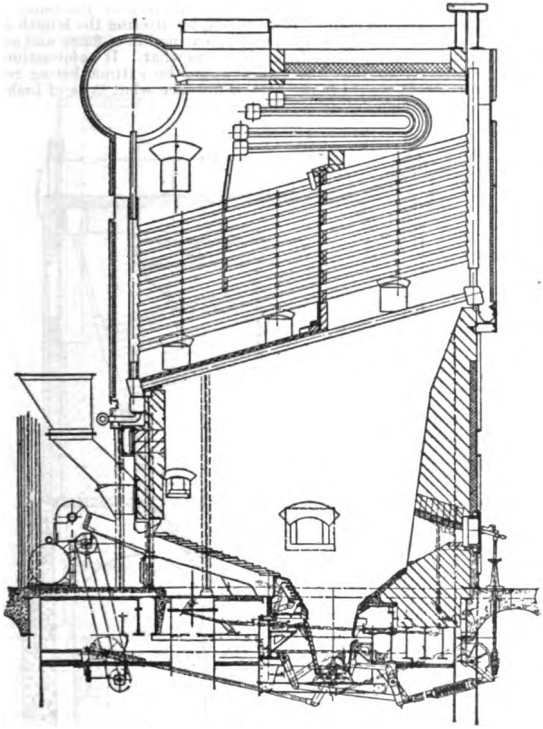


FIG. 4.—B. & W. marine type boiler with superheater, and Westinghouse stoker with clinker crusher.

BOILERS

7. Boiler types: in the following classification modern types only are considered.

- **Fire Tube...**
  - Horizontal return tubular (Fig. 2).
  - Scotch (Fig. 3).
  - Continental and other internally fired types (Fig. 3).
- **Water Tube.**
  - **Definite circulation path.**
    - B. & W..... Rust Stationary (Fig. 5). Marine (Fig. 4).
    - Heine, etc., etc., and 7 Yarrow Thorneycroft. Stirling (Fig. 6).
  - **Field Tubes.....** Niclausse

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All types give efficiencies not differing widely when subjected to the same kind of furnace and flame conditions, the structure having less inherent influence upon efficiency; the cross-baffle types have a slightly higher efficiency, due to greater turbulence of the gas flow over the tubes. But inasmuch as the structure may influence very materially the conditions of combustion, by restricting combustion spaces, by altering the length and the hydraulic mean depth of gas passages, and by extinction of flame and accumulation of dirt, it may alter the efficiencies somewhat. If combustion could be entirely complete, so that the flame would be extinct before reaching any heating surface, it would make little difference what type of boiler were employed so far as efficiency is concerned.

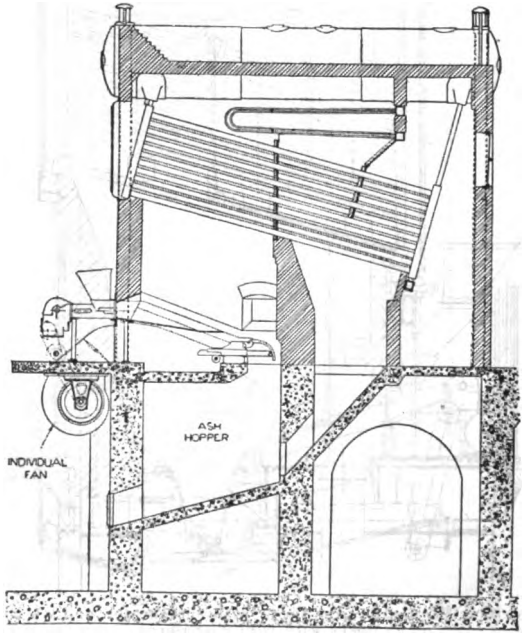


FIG. 5.—B. & W. stationary type boiler with superheater, and Riley stoker.

8. **Fire-tube boilers** are cheapest in first cost, but lowest in capacity for space occupied; in general they are the most difficult to keep in good operating condition, especially with dirty water, since the water space is not accessible. The internally fired boilers such as the Scotch and the Continental (or similar) types are somewhat superior in capacity, but not up to the water-tube type. As a class, fire-tube boilers, from the standpoint of safety, are least desirable, as they carry a large body of hot water, storing considerable energy to be liberated at the instant of rupture.

9. **Water-tube boilers** are much lighter and smaller per unit of capacity, and higher in first cost than tubular boilers, but easier to maintain inasmuch as the water surface is all practically accessible, either for hand cleaning or for turbine tube cleaners. They are very safe, having very small water storage

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(subdivided into many smaller bodies by the tubes), and are made up almost entirely of the strongest natural shapes—cylindrical—with little or no stayed surface. There are practically no records of serious accidents resulting from the explosion of water-tube boilers.

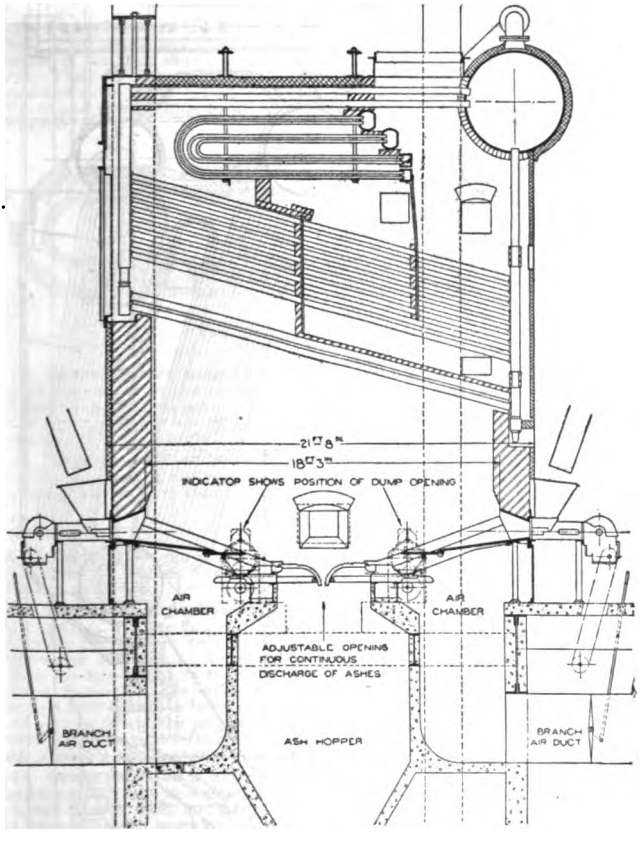


FIG. 6.—Duplex stoker setting for obtaining high combustion efficiency and extremely high boiler ratings.

10. Field-tube boilers are almost unused except for the French marine boiler known as the Niclausse. The principal objection to their use is the uncertain and spasmodic nature of the circulation which may partake of the nature of flash generation, alternating with periods of flooding with water, causing strains due to rapid and unequal expansion and contraction.

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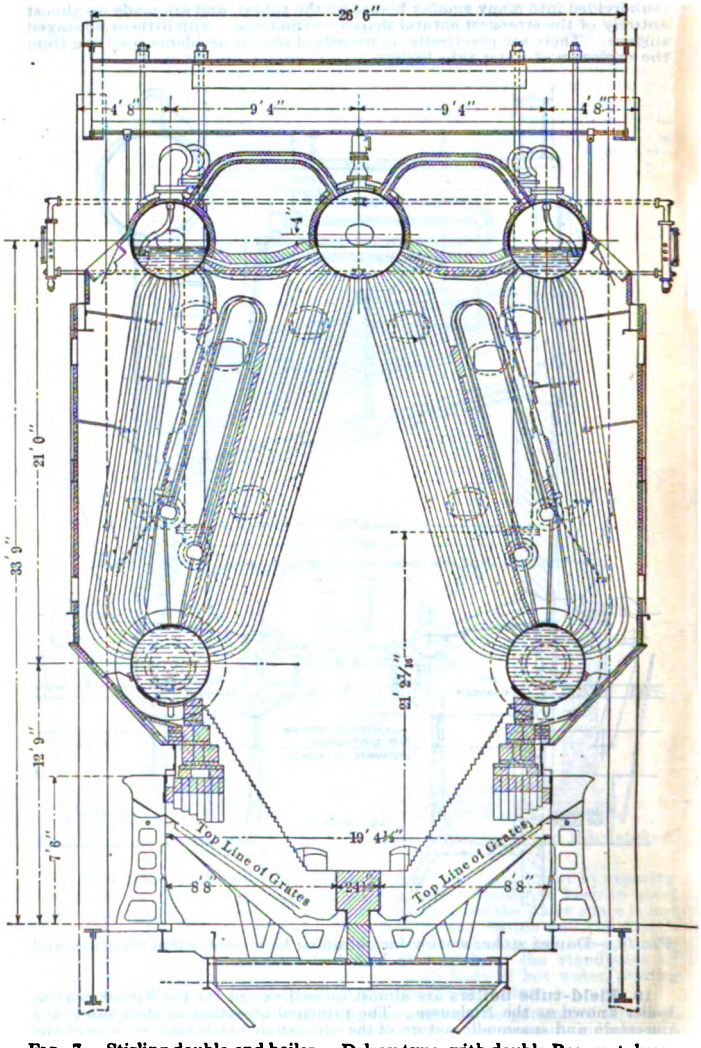


FIG. 7.—Stirling double-end boiler. Delray type, with double Roney stokers.

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11. **Flash generators** are at present unused except for steam automobile boilers and some torpedo boats. In American power stations they are unknown. However, if any standard boiler, such as the B. & W. or Stirling, be forced much above its normal rated capacity, the generation, in the lower rows of tubes at least, becomes of the flash type by reason of the extreme conditions.

12. **Superheaters** are of two general types: self-contained, and separately fired. The separately fired superheater is unpopular in America, chiefly because it has not shown such pronounced economies as the self-contained type. The two types of self-contained superheater are the plain tube and the protected tube types. To the former class belong the Heine, the B. & W. (Fig. 5) and the Stirling; to the latter class belong the Foster (Fig. 8) and the Schwörer.

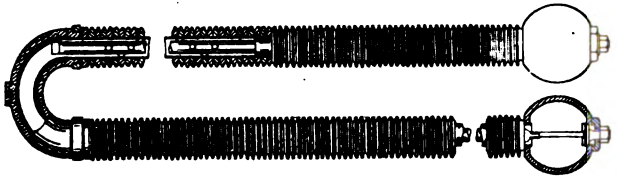


FIG. 8.—Foster superheater.

13. **Superheaters may be located** (usually) between the first and the second passes, or in the breeching. With later boilers of the ordinary stationary types the first position is popular. With the marine types now sometimes used in power stations, the latter position is satisfactory, as the gases leave the boiler at a higher temperature (see Marine B. & W. boiler, Fig. 4).

14. **Heating surface is defined as** any surface in a boiler or superheater which is exposed to hot gases on one side and water or steam on the other. In water-tube boilers the heating surface is defined as

$$\frac{\pi d l n}{12} + \frac{\pi D L N}{24} \qquad \text{(sq. ft.)} \qquad (3)$$

where d = outside diameter of tubes in in. l = length of tubes in ft., n = number of tubes, D = outside diameter of drums in in. L = length of drums in ft. and N = number of drums, headers not included.

15. **Rating of superheaters.** Superheaters are not usually rated by sq. ft. of surface, but are figured for each case. A good average rule is 15 sq. ft. of heating surface per boiler h.p., for unprotected tubes; 18 sq. ft. of heating surface per boiler h.p., for protected tubes. The reason for using larger figures for superheaters than for steam-making surface is that heat transmission is much more difficult between gas, iron and gas, than between gas, iron and water, or between gas, iron and vapor, the latter two conditions obtaining in the boiler proper. The protected tubes interpose an additional resistance to heat transfer because of the cast-iron protection rings, the roughness of which also materially increases the thickness of the dead gas film.

16. **Grate surface** is any surface upon which coal is being burned. In hand-fired furnaces this amounts to the horizontal dimensions of the furnace, side wall to side wall, and front wall to bridge. With the automatic stoker, the term becomes more or less anomalous, since part of the surface may be used exclusively for coking, and the grates may not be horizontal; and part of the grates may be used only for accumulating clinker and ash. With underfed stokers, coal is not burned upon the grates to any appreciable extent. The term is useful for comparison, if the projected area of the furnace is used in each case.

17. **The ratio of heating surface to grate surface** was once considered important and was generally made 60 to 1 when good coals were used. This ratio shows a tendency to decrease to 30 to 1 or 40 to 1 recent installations, particularly with stokers intended for forcing to high capacities, or

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where low-grade fuel such as culm, or No. 3 buckwheat is burned.

18. The value of the boiler h.p. is at present 34.5 lb. of water evaporated from and at 212 deg. Fahr., per hour; this is equivalent to 33,479 B.t.u. per hour. A unit proposed to eliminate this somewhat illogical unit, is the **myriawatt,*** a multiple of the watt, having a value of 34,150 B.t.u. per hour, about 2 per cent. larger than the boiler h.p. It would be better to eliminate these units altogether, and rate the boiler in square feet of heating surface.

19. Evaporation. Taking dry coal, the actual evaporation per lb. is,

$$E = \frac{W}{w} \tag{4}$$

$$E' = EF \tag{5}$$

$$F = \frac{H - h}{970.4} \tag{6}$$

E = actual evaporation
E' = equivalent evaporation
F = factor of evaporation
H = total heat of steam at boiler pressure and quality.
h = heat in the feed water = feed temperature − 32.
W = lb. steam per hr.
w = lb. dry coal per hr.

970.4 = latent heat at atmospheric pressure = heat to convert 1 lb. of water to steam, from and at 212 deg. Fahr.

Or the above evaporation may be used "per lb. of combustible," substituting lb. of combustible per hour in place of lb. of dry coal per hour. All temperatures are expressed in deg. Fahr., and all pressures in lb. per sq. in., and all heat in B.t.u.

20. Losses in boilers comprise: (a) sensible heat escaping in flue gases; (b) sensible heat lost in hot ashes; (c) radiation of heat to external air from boiler setting; (d) incomplete combustion; (e) excess air. Theoretically some of these losses are avoidable. Actually, about the following proportions hold good in recent practice.

Heat in coal	100 per cent.
Heat absorbed in steam (overall efficiency)	72 to 80 per cent.
Stack loss, sensible heat only	10 to 15 per cent.
Incomplete combustion	3 to 8 per cent.
Hot ashes	Negligible
Radiation and leakage	5 to 7 per cent.

21. The combustion efficiency of automatic stokers runs as high as 96 to 97 per cent. and is maintained up to a very high rating in some cases. That of a hand fire is seldom over 90 to 92 per cent. and generally much less, due to inevitable carelessness in operation.

22. Radiation is kept down by thorough lagging of exposed parts and by the usual double-walled construction of boiler settings (Figs. 5 and 6). It does not vary greatly for any type of boiler, but is reduced somewhat by setting in batteries instead of singly.

23. Excess air is caused by the slight vacuum in the setting due to draft; it can be reduced by painting or white-washing the setting and stopping up all cracks between metal and brick with plastic asbestos. In some cases enamel brick or sheet-iron settings are used, but the expense is not generally justified from this point of view alone. Another method of reducing **setting infiltration** is by the use of balanced-draft systems; in these the methods of forced draft, and natural or induced draft are so employed as to give practically zero pressure in the fire-box, by this means reducing the average difference of pressure from atmosphere, over the whole setting.

24. Furnace efficiency is expressed by the formula

$$\text{Furnace efficiency} = \frac{\text{Combustible burned}}{\text{Combustible fired}} \tag{7}$$

Combustible burned = (Combustible fired) − (Combustible in ash) − (Combustible in unburned gas) − (Combustible in soot). (8)

* Stott and O'Neill. p. 411, *Trans.* A. I. E. E., Vol. 32, 1913.

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B.t.u. Combustible fired = (lbs. dry coal) × (B.t.u. per lb. [by calorimeter]). (9)

B.t.u. Combustible burned = (combustible fired) − (B.t u. per lb. of ash) × (lbs. ash) − (B.t.u. per lb. of soot) × (lb. of soot) − (B.t.u. in unburned gases). (10)

The last item is derived from the flue-gas analysis and as it always involves several assumptions, its accuracy is not very certain.

25. Boiler efficiencies. In Fig. 9 the lower curves show the amount of coal burned per square foot of grate surface at the corresponding capacities and efficiencies. The upper curves show the efficiencies when the number of pounds of coal indicated by the ordinate produce the capacity indicated by the abscissas.

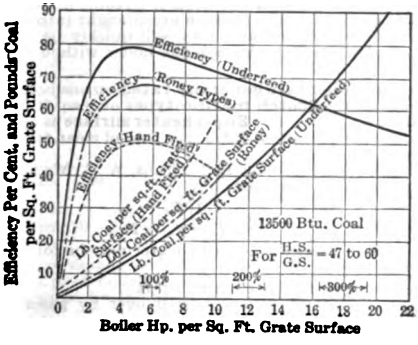


FIG. 9.—Boiler efficiency.

26. Combined furnace and boiler efficiencies. The table below gives the pounds of water evaporated per pound of coal, and the pounds of coal required per boiler h.p. hr. with coals of various heat content and with boiler installations having varying combined boiler and furnace efficiencies.

B.t.u. per lb. dry coal	50 %		60 %		70 %		80 %	
	Evaporation per lb. coal	Lb. Coal per boiler h.p. hr.	Evaporation per lb. Coal	Lb. coal per boiler h.p. hr.	Evaporation per lb. coal	Lb. coal per boiler h.p. gr.	Evaporation per lb. coal	Lb. coal per boiler h.p. hr.
8,000	4.142	8.33	4.971	6.94	5.799	5.96	6.627	5.20
9,000	4.660	7.41	5.592	6.18	6.524	5.28	7.456	4.63
10,000	5.224	6.60	6.269	5.50	7.314	4.72	8.359	4.13
11,000	5.695	6.06	6.834	5.05	7.973	4.33	9.113	3.79
12,000	6.213	5.56	7.456	4.63	8.698	3.97	9.941	3.47
13,000	6.731	5.12	8.077	4.27	9.423	3.66	10.769	3.20
14,000	7.249	4.76	8.698	3.97	10.148	3.40	11.598	2.98
14,500	7.508	4.60	9.009	3.83	10.511	3.28	12.012	2.87

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Efficiencies at head of columns are combined boiler and furnace efficiencies. Evaporation is given in pounds of water "from and at" 212 deg. Fahr. per lb. of dry coal. The heating value can also be taken for coal "as fired" whence the "evaporation per lb. of coal" and the "pounds coal per boiler h.p. hr." will also be referred to coal "as fired." This latter use of the table will contain a slight error due to the absorption of a portion of the heat by the moisture in the coal.

27. The failure of a furnace to burn all of the combustible is due to two principal causes: (a) molecules of oxygen are not brought into contact with all the particles of combustible material; (b) the temperature may be too low for ignition when they are in contact. The first condition is found where some of the fixed carbon in the lumps of coal becomes surrounded by a coating of fused ash, so that the air never reaches it during the time that the lump is upon the grate. Another cause, in the case of bituminous coal, is the lack of proper mixture of the volatile matter with air. The second condition is found as a result of the first, if streams of stratified hot combustible gas and air leaving the furnace are brought into contact with the comparatively cold heating surface, they will quickly be chilled below the ignition point, and will sweep through the boiler without further combustion taking place.

28. Water-tube boilers are generally rated on one boiler h.p. for each 10 sq. ft. of heat surface; **Scotch marine types** on 8 sq. ft., and **horizontal return-tubulars** on 12 sq. ft. **Superheater surface** is usually based on a transmission coefficient of 5 to 8 B.t.u. per deg. of mean temp. difference per sq. ft., per hour.

An empirical formula given by Bell (Trans. A. S. M. E., May, 1907) is,

Sq. ft. superheating surf. per boiler h.p. =

$$S_s = \frac{10T_s}{2(T_g - T_o) - T_s} \tag{11}$$

The temperature of gases at the superheater may be found from the following relations:

S_s = superheater surface per b.h.p., sq. ft.
S_o = per cent. of total surface passed over by gases before reaching superheater.
T_s = superheat, deg. Fahr.
T_o = saturated steam temp., deg. Fahr.
T_g = temp. of gases at superheater, deg. Fahr.

$$(0.172S_o + 0.294)(T_g - T_o)^{0.16} = 1 \tag{12}$$

These two formulæ are based on the following assumptions: constant coefficient of heat transmission; furnace temperature 2,500 deg. Fahr.; flue temperature 500 deg Fahr.; steam pressure 175 lb. gage; one boiler h.p. equivalent to 10 sq. ft. of heating surface.

29. Boiler design. Since the efficiency of boilers is so little influenced by the disposition of heating surface, comparatively little original designing can or should be done outside of standard forms. For central-station work, the water-tube boiler has practically the whole field, the specifications for a boiler therefore look more to the safety and reliability, by rigorous attention to materials, than to the actual detailed design. The management of the furnace and combustion have much more to do with the efficiency of a boiler, than the arrangement of heating surface.

30. Boiler settings have become more or less uniform in general type. For the water-tube boilers, a steel structure or skeleton for supporting the boiler proper, the brick walls being merely self supporting, is now usual practice. Common red brick is used for the outer walls, a double-wall construction being employed to allow for the differential expansion of inner and outer surfaces (on account of the great temperature difference), to minimize radiation by interposing dead air space, and to reduce air filtration. Wherever the temperature exceeds 1,000 deg. Fahr., fire-brick is employed for this inner lining. In some cases silocel and other insulating materials are employed between the fire brick and the red brick.

31. The baffles are always of fire-brick, of various special shapes, sometimes backed or supported on the cooler side by cast-iron bars or plates. Figs. 5 and 6 show these constructions.

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32. **The setting for tubular boilers**, generally supports the boiler; for internally fired boilers, no setting is required (see Figs. 2 and 3).

33. **The computation of superheater surface** is much complicated by the change of temperature of the flue gases at the superheater with load on the boiler, and the uncertainty of the transmission coefficient. The amount of superheater surface installed for superheats of 100 deg. to 175 deg. Fahr. varies from 13 to 20 per cent. of the boiler heating surface. Fig. 10 gives results of actual tests.

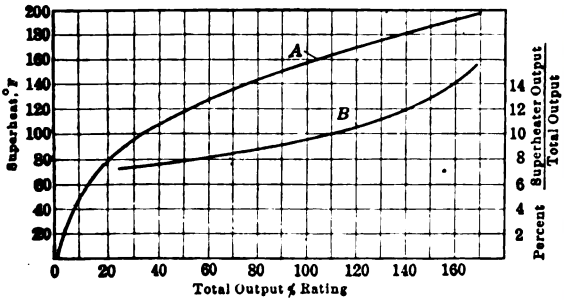


FIG. 10.—Superheater variation with output.

34. **Uptakes** are usually allowed 0.03 to 0.04 sq. ft. of cross-section (flue area) per rated h.p. of boilers attached. Where the uptakes are very long this allowance should be increased, or the loss of draft will be excessive. Where economizers are employed, the flues are best made of brick and combined with the economizer setting. Otherwise sheet-steel ducts, lagged with asbestos or other insulating material, are cheaper and more convenient. In nearly all cases the uptakes proper are made of steel. It is not necessary to line these with fire-brick unless the flue temperatures exceed 700 deg. a large part of the time; with properly operated boilers this condition need not occur. Bends in uptakes should be avoided, if possible, but where necessary should be of large radius; sudden changes of section should also be avoided.

35. **Flue areas** are based on a normal velocity of 25 to 40 ft. per second; maximum velocity, 60 to70 ft. per second. The breeching area of water-tube boilers is about 0.03 to 0.045 sq. ft. per rated boiler h.p. It is best to be generous with areas wherever possible so as to keep the draft loss low, especially for the modern high rates of driving.

36. **Safety valves** of the **pop type** are now always used, the weighted-lever type being prohibited by law in most cases. There are two principal classes: **low lift**, in which the rise of the valve is from 0.04 in. to 0.08 in.; and **high lift**, in which the rise is 0.12 in. to 0.16 in. The high-lift valves have been much more widely used in the last few years. Their principal advantage is greater relieving capacity; their possible disadvantage is with dirty or hard boiler water, priming and throwing of water from the valve.

37. **The rule of the U. S. Board of Supervising Inspectors of Steam Vessels in regard to safety valves** is expressed as follows:

$$A = 0.2074 \left(\frac{W}{P}\right) \qquad (13)$$

where A = safety-valve disc area, in sq. in., per sq. ft. of grate area under boiler,

W = evaporation, in lb. of steam per hr. per sq. ft. of grate surface, and P = absolute pressure, in lb. per sq. in. at boiler.

This is based on an assumed ratio of lift to diameter of valve of $\frac{1}{24}$ and a 45 deg. bevel seat. Real discharge capacity is not considered, and the rule is therefore not logical.

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38. Connection of safety valves. There must be **no valves between the safety valve and the boiler connection**; seats and valve discs must be of such material as will not rust together; no valves are allowed in the discharge from safety valves; in fact it is preferable to have only a muffler on the valve, and no discharge pipe at all.

39. Gage glasses of the ordinary type should be connected, preferably, directly to the steam drum and protected by wire gauze if near the level where firemen or others are working. The Klinger type of gage glass with heavy corrugated plate glass and brass casing is much safer, but more costly; the water level is much more clearly distinguished.

40. Quick-closing gage cocks operated by chain or rod are now almost universally used. The gage glass and blow-off cocks should never be so arranged that the fireman must stand close to the gage glass when "blowing down."

41. Manholes provided for entry to boiler drums, preferably in the heads where they least affect the strength, are made of pressed plate steel and fitted from the inside of the drum against a bumped lip or saddle in the drum by means of one or two bolts made fast to a dog spanning the opening on the outside. The pressure inside the boiler keeps the manhole tight, the bolts being used only to pull the cover to a seat. The **gasket** between manhole cover and seat is of asbestos, lead alloy or corrugated copper. The standard dimensions are 11 in. $\times$ 15 in.

42. Handholes are placed in mud-drums, headers, etc., which are too small to admit the body, but must be cleaned and inspected. They are made in the same manner as manholes, but the dimensions are usually 4 in. by 6 in. or 6 in. by 8 in.

43. The blow-off should be connected to the lowest and quietest place in the boiler, where the mud and scale settle, or from specially designed chambers in which the sediment is induced to collect. The blow-off pipe must be protected from the fire, as it has normally no circulation of water to protect it. Many installations have been made with a plug cock next the boiler, followed by a gate valve to prevent leakage. There are now, however, one or two successful valves on the market which do not require the additional gate valve.

44. The feed pipe should enter the boiler so that the flow is in the direction of natural circulation in the boiler. Outside the drums the feed pipes are generally of brass to eliminate the chance of a break at this point from corrosion. A **check valve** is fitted at the entrance to each drum, to prevent water flowing back.

45. The steam gage is connected to the steam space of the boiler, to prevent blocking of the pipe by scale or mud. A **condensing coil** should be applied to prevent hot water or steam from getting into the Bourdon tube of the gage. **Thermometers** are practically never used as a measurement of steam pressure, except on tests, but are much more reliable.

46. Pyrometers are used for measurement of flue gas temperature, leaving the boiler, and are very valuable aids in checking the operation and efficiency.

47. Safety plugs are made of pure Banca tin, and are so placed that the active fire will play upon them, or at least in the first pass through the tubes. They are placed about 10 or 12 in. above the danger limit of low water; they are ordinarily protected by the water, but melt in case the level falls below them. The fire side of the plug must be kept clean of soot, or it may become so protected as to be inoperative.

48. Boiler corrosion is caused either by direct oxidation of the iron by **oxygen** dissolved in the water or by reaction with some **acids** present in the feed-water, having their source either in natural acidity or from the products of decomposition of impurities introduced into the feed. Corrosion by oxidation is the more important, as the other is always avoidable by proper purification of feed water. Oxidation goes on continuously wherever dissolved air is present, and is much increased by the vibration or flexure of any particular point. The constant bending breaks off the film of iron oxides formed by the process, and exposes new surface to be attacked; for this reason pitting is commonest near joints where the flexure of some one portion of a plate is apt to be severe.

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49. Incrustation is caused by the deposit of solid matter during the heating and boiling of the water. It may be merely a mechanically entrained impurity, such as mud and sand, or it may be the result of precipitation of various salts insoluble in hot water, or by super-saturation. The **salts** of magnesia, lime and iron are those giving most trouble in boiler water. Some of these salts are soluble and cause the formation of scale by super-saturation; others are insoluble in hot water and precipitate as the water is heated.

50. Treatment of feed water. The principal salts are iron, calcium and magnesium carbonate, bicarbonates, and sulphates. The bicarbonates are usually decomposed by boiling. The general method of treatment is by adding lime (CaO), and sodium carbonate (Na_2CO_3) called in the impure commercial form, soda ash.

51. Removing the precipitation. Where the character of the water or the plant layout does not allow the treatment in a separate purifying system, these reagents are added in the boiler feed, and the precipitation takes place in the boiler, assisted by the heat. The main object in this case is to precipitate the salts as soft scale, or mud, in order that it may be readily blown out. Periodic cleaning with some kind of mechanical cleaner is necessary, however, even with feed-water treatment, as some of the hard salts are bound to stick, especially in the hardest worked tubes over the hottest fires.

52. Periodic inspection of boilers is in itself a good preventive of accident. The straight tube, water-tube boilers lend themselves most readily to thorough inspection, as every part can be seen, and the whole of the shells can be hammer tested.

53. Boiler insurance covers the possible damage done by boiler explosion. The boiler insurance companies exercise a vigorous and valuable control over the manner of operation of boilers, and by their frequent enforced inspection, prevent little flaws from becoming disastrous weaknesses.

54. Cleaning. Those operations which make for safety in the boiler generally aid efficiency. A good rule is never to allow more than $\frac{1}{16}$ in. thickness of scale to collect; and to overhaul thoroughly every part of the boiler twice a year. In a well-operated plant, with moderately good water, this generally means cleaning the two rows of tubes nearest the fire about once a month, and the remainder of the boiler, twice annually. It generally pays, both in safety and efficiency, not to use water requiring more frequent cleaning of the boiler than last stated, but instead to purify the water in separate apparatus.

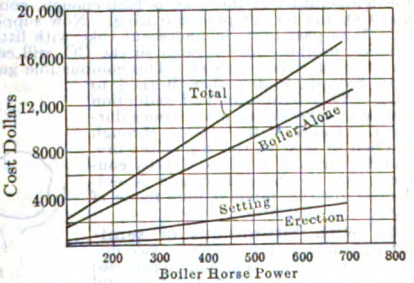


FIG. 11.—Cost of water-tube boilers.

55. The removal of soot from the outside of the tubes is usually required once a day in well-operated plants; but for high rates of forcing, and especially for low-grade fuels requiring heavy blast, the interval may be shortened to once every eight hours.

56. As far as possible, all conditions about a boiler should be kept uniform—water level constant, feed supply steady, draft well regulated, and firing (either by hand or stoker) uniform. The use of draft, pressure, steam-flow indicators or feed meters, is always valuable in this connection. Changes of load should be anticipated by gradual changes in the running of the boiler, since sudden alterations of draft or feed not only cause strains in the boiler, but loss of efficiency, thus disturbing the normal operation of the fire and flow of steam.

57. Boiler costs. Fig. 11 shows the variation in total cost of **water-tube boilers** of the B. & W. or Stirling types. The cost remains practically con-

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stant at $22.00 to $25.00 per h.p. This is partly due to the fact that most of the smaller boilers are built for lower pressures than the larger units. If all were built for high pressures, say 200 lb. gage, the cost would follow approximately the rule given below (Jan., 1921).

Cost in dollars = 950 + 18.6 × (rated h.p.) for boiler alone. (14)

58. The average setting cost for 300-h.p. to 600-h.p. units is $5.50 per h.p., and varies little. The delivered price is approximately 71 per cent., the erection cost 9 per cent., and the setting 20 per cent. of the total cost, which remains very nearly constant at about $25.00 per h.p. for horizontal water-tube boilers between 300 h.p. and 750 h.p. (Jan., 1921).

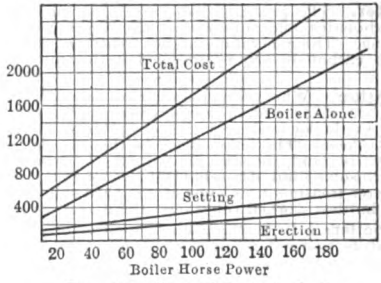


FIG. 12.—Cost of fire-tube boilers.

59. The cost of vertical water-tube boilers averages 10 per cent. less than horizontal water-tube boilers. The cost in dollars = 950 + 18 × (rated h.p.), for vertical water-tube boilers (delivered only).

60. The corresponding costs of fire-tube boilers are given in Fig. 12.

FURNACES AND STOKERS

61. Principles of combustion: Referring to Fig. 13, a stream of oxygen is shown ascending past a piece of white-hot carbon—say a piece of **coke**, or a piece of **anthracite** having practically no volatile matter. Provided the temperature of the coke is high enough, combustion takes place to CO_2 and CO, the former predominating. Now suppose this stream of CO and CO_2 flows past more incandescent coke with little or no oxygen in the immediate neighborhood. Some of the CO_2 will combine with the incandescent C and reduce to CO. This combustible gas now flows on till it finds more oxygen, and is then burned to CO_2. This oxidation and reduction may go on reversing many times during the travel of the stream through the bed of coal to the top of the fire, and the burning of CO to CO_2 by contact with the needed oxygen is evidenced by the familiar blue flame of anthracite coal fires.

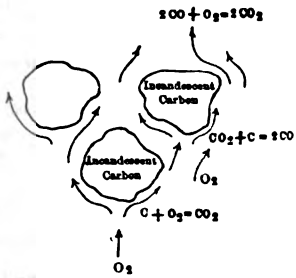


FIG. 13.—Elementary combustion of fixed carbon.

62. With bituminous or semi-bituminous coals, there are two distinct phases in the combustion process: first, on heating, the distillation and burning of the volatile hydrocarbons, leaves behind a mass of porous coke; second, the burning of this coke takes place exactly as the anthracite is burned. The distillation of the volatile matter introduces, therefore, a period during which the coal absorbs heat instead of giving it out. The extra volume of gas given off requires a freer supply of air than the hard-coal fire.

63. The two great requirements for efficient combustion are: (a) thorough "scrubbing" of the coal (or coke and volatile gases) with the right amount of air, so that each particle of combustible receives its necessary oxygen within the smallest possible space of time; (b) the maintenance of both air, gases, and coke at a temperature above the ignition point.

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64. Types of furnace and stoker: Hand firing always necessitates a horizontal or slightly inclined grate, so that coal may be fired through open doors all over the surface of the grate; most of the air is fed through the fire from below the grate. In the case of anthracite practically no air is admitted over the fire, because the compact nature of the small sizes of anthracite makes the use of air blast generally a necessity, and more than enough air can be supplied from below the grates. With bituminous coal, not enough air can be supplied from below, and some must be admitted by way of the fire doors or other openings for the purpose above the fire. The required reverberatory action for soft coals must be obtained chiefly by methods of firing. Regenerative action can be improved by the use of Dutch oven furnaces, in which the whole furnace is roofed over with fire-brick, which reflects heat instead of absorbing it, raising the temperature of the furnace. The soft-coal furnaces should always have as high a combustion chamber as possible, but with anthracite coals 18 in. is sufficient. Fig. 14 shows one type.

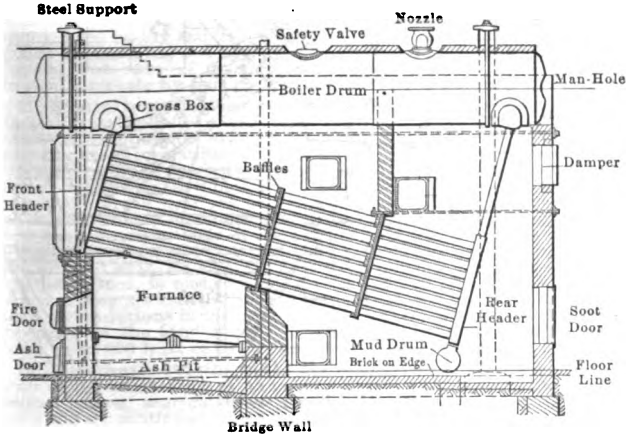


FIG. 14.—Hand-fired grate.

65. The overfeed stokers are those in which coal is fed somewhat in the manner of hand firing; green coal is pushed in at one end, or side of the combustion chamber, coked under a combustion arch, and finally burned to ash in a continuous progress across the furnace, the combustion of fixed carbon taking place upon the grates. The best known inclined types are the Roney, Murphy, Model, Detroit and Wetzel. Fig. 15 shows the Roney type; coal is fed in at the top and worked down by gravity and the continual rocking of the grate bars.

66. The chain grate types are the B. & W., Green, Coxe, Illinois, etc. Fig. 16 shows a typical chain grate.

67. The underfeed stokers supply coal from below the fire, coke it as it approaches the incandescent top bed, and drive the gases, along with the blast air, through the white-hot coke on top. No combustion arches are required and there are no grate bars, strictly speaking, as little or no combustion takes place on iron—only upon a bed of coal.

68. Types of underfeed stokers. The Jones was the original of this type, followed by modifications utilizing gravity as well; the earliest one of the latter type is the Taylor, followed by the Riley and the Westinghouse underfeeds. Lately, extension grates of the overfeed type and continuous dumping devices have been incorporated in this type of stoker, lowering the combustible content in the ash, and reducing the operating labor.

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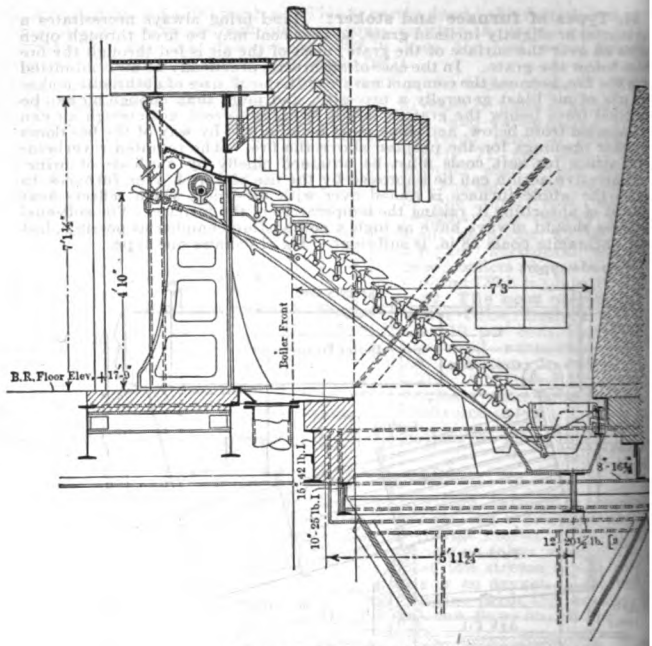


FIG. 15.—Roney stoker.

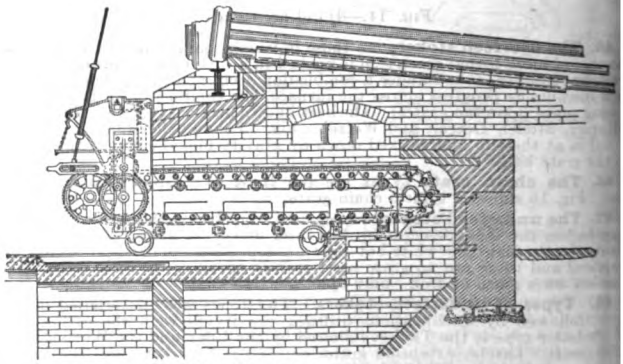


FIG. 16.—Chain-grate stoker.

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69. Grates for hand fires are of three types, stationary, shaking and dumping. Stationary bars are of three principal forms: (a) plain girder-shaped straight bars, spaced from each other ¼ in. or ½ in. by lugs, for air supply; (b) herringbone bars—two straight girder bars about 4 in. to 6 in. apart, cast with herringbone-shaped tie ribs; (c) pinhole bars, for burning sawdust, fine dust and culm, tan bark and similar materials. Rocking and shaking grates are made in a multitude of variations of these simpler forms; and are so arranged that the bars may be rocked in groups, to aid in cleaning the fire, or overturned to dump entirely.

70. Hand stoking of hard coals is done in the following manner. Coal, generally of small size (No. 2 or No. 3 buckwheat), is thrown well over the fire, and maintained about 6 in. to 8 in. thick and under considerable blast (1.5 in. to 2.5 in. of water). As fast as a hole blows through any portion, it is covered with fresh coal. This implies frequent firing, and in order to minimize the inrush of cold air at open fire doors some form of balanced draft is very desirable. Portions of the fire are allowed to burn out and are then dumped bodily and fresh fire raked over the bare grate. **With shaking grates** the dumping periods may be farther apart—4 to 8 hr., depending on the coal and rate of firing, as part of the ashes are removed at more frequent intervals by shaking the grate without opening the fire doors.

71. Bituminous coal can be hand fired in two ways: the alternate and the coking methods. In the first method, one side of the fire is at the period of hottest combustion while firing green coal on the other, to provide the necessary heat to volatilize and ignite the large volume of gas given off. When this green coal has finished giving off gas and becomes well coked and white hot, the other side, now burned out, is fired. In the coking method, the front part of the grate near the fire doors is made solid and is called the dead plate; green coal is fired upon this, under a coking arch, and receives enough heat from the main body of the fire and from this arch, to become coked. The gas thus given off passes out from the coking arch over the hot part of the fire, is mixed with air admitted over the fire, and thus ignited. The green coal, now coked, is pushed back over the hot part of the fire. As portions burn out, they are dumped and fresh coke raked over the bare grates. There are many variations in the manner in which these operations are performed, depending on the kind of coal. One man can ordinarily take care of one boiler up to 600 h.p., or two boilers at the utmost.

72. Automatic stoking in the overfeed type occurs almost in the same order as the hand firing of bituminous coal, except that all the processes, feeding, coking, segregation of ash, and sometimes dumping, are done by power and are continuous, instead of intermittent. The advantage in avoiding irregularity in the processes is obvious.

73. Automatic stoking in the underfeed type requires no regenerative devices in the furnace (such as the coking arch), since the gases and the air are mixed by passing through the bed of coal together and are finally heated by direct contact with the incandescent coke, before issuing into the furnace. The underfeed stokers are capable of almost unlimited forcing without serious loss of furnace efficiency, and are much lower in maintenance costs than the overfeed types, as no hot fire is carried on cast-iron parts.

74. Maintenance costs of stokers. The following costs applied in 1914, but should be doubled for 1920–21 conditions. The maintenance of Roney stokers with good coal, varies from about $0.10 to $0.12 per ton fired; the Murphy, Model, Detroit, Wetzel and Wilkinson vary from $0.11 to $0.14, the higher cost being due to the use of long bars in the fire, which are injured only in about the lower third, necessitating the scrapping of about two-thirds of the bars practically uninjured. With the Roney finger grate, the parts actually in the fire are separately removed, and consequently the efficiency of use of the metal is higher. Chain-grate stokers are comparable in maintenance with the Murphy type. Jones stokers require about $0.04 to $0.06 per ton fired for maintenance, and the Taylor stoker from $0.025 to $0.04 depending on the coal. Highly volatile coals, which must be fired thinner on account of clinkering, use up more iron, as the heat is nearer to the fingers and retorts.

75. Stoker labor. One stoker operator to each four stokers, and one coal passer to rake up siftings for each five stokers is good practice for the

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Roney type. The size of the stoker makes comparatively little difference, and hence the larger the stoker the better. One stoker operator for 6 stokers, and one coal passer for raking siftings to 6 stokers, is good practice for the Green or B. & W. types. One stoker operator to 15 stokers is needed for the Riley and similar types but no coal passers, as there are no siftings. The Jones type requires about the same labor as the Roney as the ashes must be raked out by hand.

76. The rate of combustion for hand fires is normally 10 lb. to 12 lb. of coal per sq. ft. of grate for anthracite, and 15 lb. to 20 lb. for bituminous coals. Under forcing the rate may go as high as 80 lb. per sq. ft. of grate, with forced draft. For power plants the usual maximum is 40 lb. to 50 lb. of soft coal.

77. Natural or chimney draft is common for bituminous coals. On hand fires 0.3 in. to 0.6 in. water draft at the breeching will generally produce rated capacity from the boiler; 0.3 in. draft at the breeching will produce rated capacity on the overfeed slope-grate types with high percentage of air space (35 per cent. to 45 per cent.). With the restricted types (Wilkinson) and the chain-grate stokers, where the air space is only 8 per cent. to 15 per cent., the required draft to produce rating is usually 0.4 in. to 0.5 in.

78. Forced draft with underfeed stokers and anthracite hand fires is practically a necessity, as the resistance through the fires is very much greater (Par. **80**). The small sizes of anthracite pack very closely, and in 6 in. or 8 in. thickness may offer as much as 1 in. to 2 in. difference of pressure above and below the fire. In the underfeed stokers the fire is much thicker than in the overfeed type (the latter is about the same as hand-fired bituminous grates or 10 in. to 14 in.), or usually about 2 ft. 6 in. or 3 ft. thickness of fuel bed.

79. The amount of air required varies with the volatile content of the coal. The combustible constituents are carbon, hydrogen and sulphur. As far as heat and air supply are concerned, the carbon and hydrogen alone are important, the sulphur seldom exceeding 3 per cent. being low in heat value.

$$C + O_2 = CO_2 \tag{15}$$

$$\underbrace{2H_2}_{2\text{ vol.}} + \underbrace{O_2}_{1\text{ vol.}} = \underbrace{2H_2O}_{2\text{ vol.}} \tag{16}$$

The combining weights are in the proportions of the molecular weights, so that

$$12\text{ lb. } C + 32\text{ lb. } O_2 = 44\text{ lb. } CO_2 \tag{17}$$

$$1\text{ lb. } C + \tfrac{32}{12}\text{ lb. } O_2 = \tfrac{44}{12}\text{ lb. } CO_2 = 3.67\text{ lb. } CO_2 \tag{18}$$

Air is 20.9 per cent O_2 and 79.1 per cent. N by volume, and 23.6 per cent. O_2 and 76.4 per cent. N by weight, so that, as 1 lb. C requires 2.67 lb. O_2, it will require $\frac{76.4}{23.6} \times 2.67 = 11.30$ lb. of air per lb. of carbon. Similarly, hydrogen requires 34 lb. of air per lb. Then the air required per lb. of any coal will be given by

$$(\text{fraction C per lb.}) \times 11.3 + (\text{fraction H per lb.}) \times 34 = \text{lb.} \tag{19}$$

air required per lb. of coal.

The theoretical amount cannot be used because mixing is imperfect. Usually 18 lb. of air per lb. of coal are supplied for underfeed stokers and 20 lb. to 24 lb. for overfeed and hand fires.

80. Automatic damper regulators are used to maintain substantially constant boiler pressure under variable load. A diaphragm operated by steam pressure controls a pilot valve admitting water or oil under suitable pressure to a cylinder which in turn operates the damper lever. If increase in load causes drop in pressure, the diaphragm and pilot cause the pressure cylinder to open the damper wider, increasing the draft and the rate of combustion, thus making more steam to recover the proper steam pressure; and *vice versa*. This device may be employed in the stack or breeching for natural draft; or it may control the fan-engine throttle for forced or induced draft, producing the same results.

81. In the balanced-draft systems, a steam pressure regulator controls the forced-draft fan, and a combustion-chamber pressure regulator controls the stack damper or induced-draft fan, so as to maintain zero pressure difference over the fire. This is specially advantageous for hand firing, as the

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fire doors may be opened and shut without a rush or cold air over the fire. It is also a convenience with any forced-draft stoker.

82. The accessories of the automatic stoker consist of the forced-draft fan (if required), the stoker engine, and usually, for overfeed stokers—a slice bar and a poker, needed occasionally for obstinate clinkers. In the later types of underfeed stokers, automatic dumping devices are attached, which eliminate the need of hand manipulation of the fire almost altogether (Fig. 5).

83. The stoker engines required with all stokers except the Jones and the Wilkinson, may be of any standard type. The slope-grate overfeed stokers require about 1.5 to 2 h.p. per stoker, the highest being for the largest sizes—say 150 in. in width. Chain grates require 2 to 3 h.p.; underfeed stokers, 3.5 to 4 h.p. per stoker. The Riley requires about 0.4 h.p. per retort. The Jones type has a steam cylinder attached individually to each plunger and requires no other drive. The Wilkinson type generally has a hydraulic cylinder operating each stoker.

84. Furnace efficiency is defined in Par. **24**. Its value for hand fires may be brought up to 94 or 95 per cent. but seldom runs higher than 88 per cent. in regular operation. Automatic stokers can be made to operate at efficiencies as high as 96 to 97 per cent. It is a question chiefly of adequate air supply, intimate mixture of gases, and high temperature.

85. Flue-gas analysis. The Orsat apparatus is the simplest and commonest means of analyzing flue gases. It appears in several forms, all of which employ some form of graduated glass gas-measuring chamber, usually waterjacketed, and has means for exposing the sample of gas successively to solutions of potassium hydroxide, potassium pyrogallate, and cuprous chloride (generally the acid solution), for removing CO_2, O_2 and CO, respectively. The gas is returned to the measuring chamber after each absorption, to measure the reduction of volume. Several automatic machines have been devised for measuring and recording CO_2 content in flue gases continuously; but it is now well known that CO_2 measurement alone is an insufficient indication of boiler efficiency. Flue temperature and sometimes the full gas analysis are desirable. The absorption of CO is particularly troublesome, as a rule, because the cuprous chloride must be used fresh, and is apt to throw off the absorbed CO if diluted; this also may happen in the Elliott apparatus. **The Elliott apparatus** differs from the Orsat in using long burettes and pipettes for greater accuracy, and the pouring of the absorbents through the absorbing chamber by hand; also, an explosion pipette for measuring the unburned hydrocarbons is added. **The Hempel apparatus** is still more accurate and refined, but is strictly a piece of laboratory apparatus. The Orsat type is made in easily portable form for use at the boiler.

86. Smoke consists chiefly of unburned carbon suspended in the flue gases; it may be in the form of particles of unburned coke blown up from the fire by heavy driving or high blast, or in the finely divided lamp-black form, developed by the breaking up of hydrocarbon gases, deficient in air, and exposed to high temperature. The latter form is chiefly indicative of bad combustion; the cure consists of thorough mixing of volatile matter and air in the furnace, and the maintenance of a high temperature of this mixture until combustion is complete, or in other words, until there is no more flame. In so far as any furnace or method of firing accomplishes these two things, in that degree it will be smokeless.

87. Specifications for stokers should cover the following: (a) general, and terms of delivery and erection; (b) drawings of stokers and dimensions of boilers to which they are to be attached; (c) operating conditions of boilers and rating; (d) general description of stokers; (e) dampers, doors, drive, and labor used; (f) fan requirements, foundations, air ducts and brickwork; (g) tests and operating conditions for tests, including full description and proximate analysis of coal to be used; (h) guarantees, capacity, efficiency, labor to operate, gas analysis, smoke, maintenance; (i) time of shipment, price and terms of payment; (j) detailed description of stoker and all parts.

88. The cost of automatic stokers per rated h.p. of boiler (May, 1920) varies but little with size, as most of the stokers are made up of parts such that increase in size means merely increase in unit structure. The price is given delivered but not erected, although superintendence of erection is included; common labor for erection is furnished by the purchaser.

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The cost of Roney and other step-grate stokers is from $6.50 to $8.00 per rated boiler h.p., average $7.50; chain grates, $13.00 to $20.00, average $16.00; underfeed (Jones type), $7.00 to $11.00, average $8.50; underfeed (gravity plunger), $12.00 to $16.00, average $14.50.

89. **The forcing capacity** of these different types is extremely variable; the overfeed step-grate types usually cannot exceed 200 per cent. of rating; the chain grates are about the same. The underfeed types are readily reaching 300 per cent. and over. The cost per rated h.p. is therefore not entirely fair as the sole criterion.

90. **Cost figures from a very large stoker installation** using three types are as follows, complete with blowers and stoker drive (1920).

	Rating	Cost per h.p.	Rating	Cost per h.p.
Step grate.....	100 %	$7.00 to $7.50	200 %	$3.50 to $3.75
Chain grate with blast...	100 %	$16.00	266 %	$6.00
Gravity underfeed.....	100 %	$14.00	325 %	$4.00

The weight of the step-grate stokers is about 500 to 550 lb. per rated boiler h.p.; chain grates, 1,300 to 1,400 lb.; underfeed types (gravity), 550 to 630 lb.

CHIMNEYS

91. **Chimney draft** is based upon the difference of specific gravity of cold air and heated air. The column of warm air in the chimney exerts a pressure per sq. ft. at the base of $h\gamma$, where h is the height in feet and γ is the density of hot gases in lb. per cu. ft. The pressure of the outside air for the same height is $h\gamma_2$, where γ_2 is the density of cold air in lb. per cu. ft. The motive force is therefore the difference of these two, or $h(\gamma_2 - \gamma_1)$, in lb. per sq. ft.

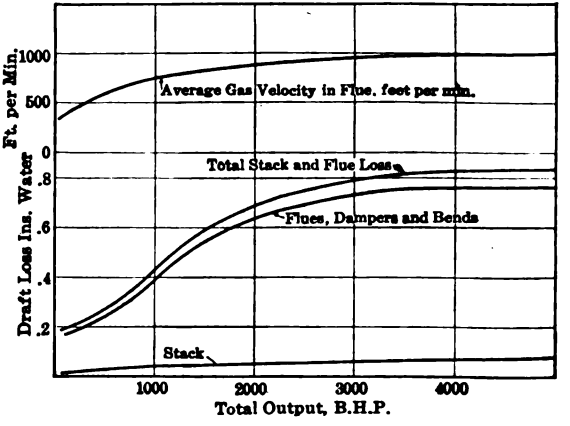


FIG. 16a.—Draft loss in flues and stacks.

92. **Formula for chimney draft.** For ordinary use,

$$D_1 = 0.255\, P_2 H \left(\frac{1}{T_2} - \frac{1.04}{T_1}\right) \qquad (20)$$

Where H = height of chimney in ft., D_1 = intensity of draft, inches of water, T_1 = absolute Fahr. temp. of chimney gases, T_2 = absolute Fahr. temp. of outside air, and P_2 = observed barometric pressure, ins. mercury.

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93. Draft required. The required draft is difficult to compute accurately, since it is made up of the sum of draft losses for accelerating the gases, friction loss through boiler, flues, and stack, and loss of head at each change of section, turn, and air leakage into the system. Fig. 16*a* shows the draft losses which should ordinarily result in normal design, from the boiler, breeching on, and also indicates the flue velocities for computing areas. The stack velocities should run 1400 to 1500 feet per min.

94. Boiler draft loss. Fig. 16*b* shows the draft required from furnace to breeching, for stokers using forced draft, and is based on 0.1 in. draft over the fire; the blast pressure does not affect the problem, in this case. Fig. 17 shows the draft required between ash-pit and breeching, for hand-fires, and stokers using natural draft. The draft loss through economizers varies from 0.25 in. to 0.75 in.

95. Total draft. The total draft will be the sum of the draft required for flues, etc., from Fig. 16*a*, and that required for the boiler at maximum rate of driving, from Fig. 16*b*, or Fig. 17. Formula 20 may be rewritten, for convenience in solving for H,

$$H = \frac{D_1}{0.255\, P_2\left(\frac{1}{T_2} - \frac{1.04}{T_1}\right)} \qquad (21)$$

D_1 will be the total draft found above, and H the corresponding height. The figures thus obtained will be on the safe side, a very desirable condition for the draft system. A draft system made too small is an exasperation in operating and an expensive thing to correct, specially now that the tendency is always toward higher forcing.

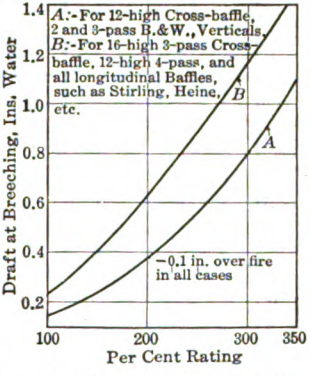


FIG. 16*b*.—Draft loss through boilers.

96. Stack capacity. It will be noted that the old method of rating in h.p. is not employed; it is much better to design the stack on a gas basis.* For most purposes, 500 cu. ft. of hot gases per pound of coal (50 per cent. excess air, 600 deg. Fahr.) is a perfectly safe basis.

From the total weight of coal burned per hour, the total gases per minute can be obtained; dividing by the velocities given in Par. 93 and Fig. 16*a*, will give the stack and flue areas required.

97. Chimneys are built of the following materials: (a) red brick, fire-brick lined; (b) radial buff brick, fire-brick lined; (c) reinforced concrete, lined; (d) steel plate, lined; (e) steel plate, unlined. For natural draft, the radial brick, the lined steel plate and the concrete types of chimney are in general use.

98. Brick chimneys. The red-brick chimney cannot be less than 0.7 ft. thick at the thinnest portion; in other respects it is designed for stability against a wind pressure of 50 lb. per sq. ft. and against crushing. The walls, therefore, are always thicker at the bottom, and the stack is tapered. This type is not often used for power stations. Radial-brick chimneys may be 0.58 ft. thick at the thinnest part, as the brick is specially moulded; the cross-section is always circular, and tapers in the same manner as red-brick chimneys. Brick chimneys are the most durable of all the types. The fire-brick portions of lining need be carried up only 30 ft. above the grates.

99. Steel chimneys have the advantages of lightness and strength, but since they are better conductors of heat, must be lined with brick for heights over 75 ft. except in forced-draft installations. They must be carefully inspected and painted from time to time, as they are subject to deterioration by corrosion.

* A. S. M. E. Trans. 1915, A. L. Menzin.

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100. Reinforced concrete is much stronger than brick and will stand high tensile strains like the steel chimney. The stack is therefore often built straight like the steel chimney, and is always considerably lighter than brick, as it may safely be much thinner. It is usually poured in 5-ft. or 6-ft. sections, which may be carried up a section a day, making erection rapid. No lining is required other than the short section of fire-brick above the grates (30 ft.). It is one of the cheapest and most durable forms if well designed and built, but like all reinforced concrete, is dependent upon care and watchfulness during construction.

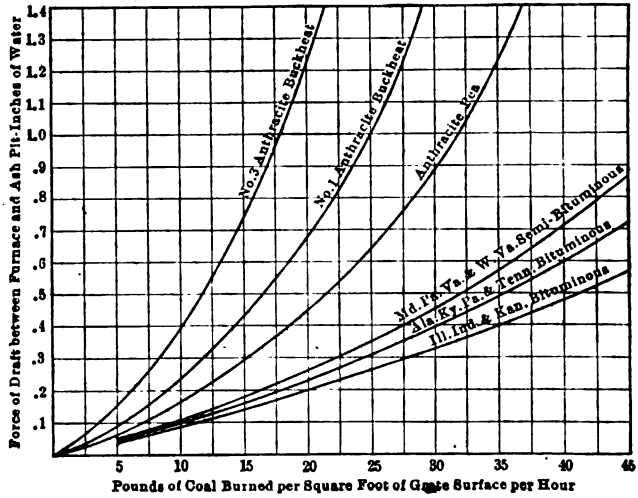


FIG. 17.—Draft for various coals.

101. Foundations for brick chimneys are now made almost exclusively of concrete, and are designed on the basis of proper bearing values, like any other foundation. They are usually spread or stepped out at the foot, in order to provide sufficient resistance to overturning from wind pressure (Par. 590).

102. Cost of Brick Stacks (1920)

Approx. boiler h.p.	Height	Diameter	Diam. square base outside	Price
85	80	2 ft. 1 in.	7 ft. 5 in.	$1345.00
135	90	2 6	8 3	1768.00
200	100	2 11	9 10	2760.00
300	110	3 7	10 2	3360.00
450	120	4 3	11 2	4020.00

Brick stacks may be figured on a basis of $24.00 per thousand for laying with masons at $1.00 per hour.

103. The cost of concrete stacks is about 5 to 10 per cent. less than brick (Par. 102).

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104. The cost of steel stacks may be figured on a basis of $0.045 per lb. of steel erected.

MECHANICAL DRAFT

105. Limitations of natural draft. From the figures in Par. **91** to **96**, it is evident that for high rates of combustion the stack becomes impracticably high, or the sensible heat loss due to high flue temperature becomes too large for economy. To mitigate this, mechanical or artificial draft of some form may be employed.

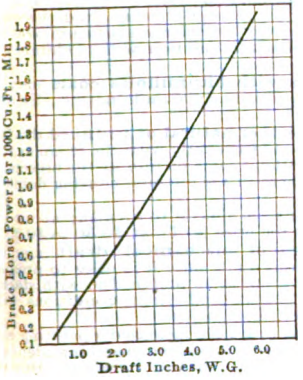


FIG. 18.—Required horse-power for forced-draft fans.

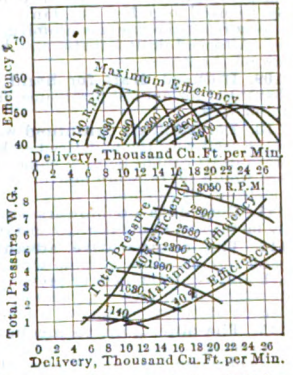


FIG. 19.—Characteristics of 24 by 30 in. forced-draft blower.

106. The theoretical pressure produced by a revolving fan wheel is given by Murgue as

$$H = \frac{U^2}{g} \qquad (22)$$

where H = maximum pressure difference, between fan suction and discharge, in feet of air; U = velocity of fan blade tips, feet per second; and $g = 32.2$, acceleration due to gravity. Air pressure in inches of water column is generally referred to in blast and draft.

$$h = \frac{SH}{144p} \qquad (23)$$

where h = inches of water pressure; S = weight of 1 cu. ft. air at 70 deg. fahr. (usual room temperature), or 0.075 lb.; and p = pressure of 1 in. water column in lb. per sq. in., or 0.0361 lb.

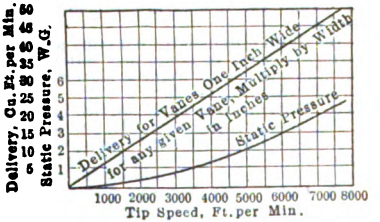


FIG. 20.—Pressure and volume of forced-draft fans.

$$U = \frac{2\pi rn}{60} \qquad (24)$$

where r = radius to tip of blade in inches and n = r.p.m. Hence

$$h = \left(\frac{2\pi rn}{60}\right)^2 S = C(rn)^2 S \qquad (25)$$

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Fig. 18 gives the h.p. required at any pressure, for average fans. The characteristics of a forced draft fan for underfeed stokers are given in Fig. 19. The static pressure and volume of any size fan, at any speed, can be found approximately from Fig. 20, which assumes similar shape of vanes, and static efficiency about 55%.

107. Forced draft. If the fan is placed so as to blow under the fire, the pressure is greater than atmospheric; this system is termed forced draft.

108. Induced draft. If the fan suction is connected to the boiler flue, and delivers to the stack, the pressure in the furnace and ashpit is less than atmospheric; this system is termed induced draft. The two systems may be used together, one fan forcing air through the fire, and the other drawing from the flue, maintaining a more or less balanced pressure over the fire. A forced draft fan also may be used, in connection with a chimney to draw off the gases.

109. Induced draft for hand fires with bituminous coals may be substituted for natural draft since the required maximum is not usually over 2 in. of water.

110. Forced draft combined with either natural or induced draft is always used with the underfeed stokers and frequently with the chain grates. Forced draft cannot be used alone, as without some suction at the breeching, there would be pressure above atmosphere in the fire-box, causing flame to issue from all openings.

111. Cost data on blowers and fans are difficult to furnish; about the only factor remaining nearly constant is the price per lb. at $0.30 to $0.35.

112. The comparative advantages of mechanical draft are: (a) greater forcing capacity than with natural draft, since it is easy to produce much greater differences of pressure than are at all practicable with stacks; (b) entire flexibility of control; (c) better combustion conditions with balanced draft arrangement; (d) low cost of apparatus.

113. The objections to mechanical draft are increased operating cost due to energy consumption by driving apparatus, and increased maintenance cost, which are balanced against the low maintenance of stacks. But the energy consumption (of steam, for turbine drive, say) is not a net loss, as it may be profitable to use the steam exhaust in feed heating, and the stack requires a certain loss of fuel due to flue gas temperature, in order to operate. This temperature can be lowered when using induced draft. **Forced-draft fans** have low maintenance costs, as they handle cool air; **induced-draft fans**, however, are likely to have high maintenance, as they deteriorate from handling hot flue gases.

PROPERTIES OF FUEL

114. Anthracite, or hard coal, contains very little volatile matter; is mainly fixed carbon and ash; is difficult to ignite; hard and bright fracture, not soiling the fingers in rubbing; oldest coal formation, being next to graphite.

115. Semi-anthracite contains a little less fixed carbon, more volatile matter; is easier to ignite and softer. **Semi-bituminous** is the next in order, having enough volatile matter to coke, with moderately long flame, and soft crumbly fracture.

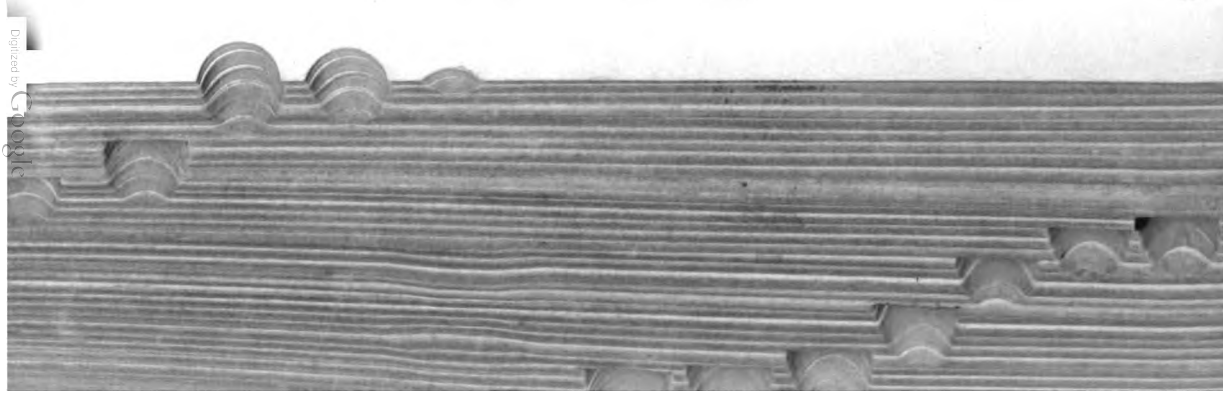
116. Bituminous coals are rich in volatile matter, which may be as high as 40 per cent.; usually fairly low in ash—5 to 9 per cent.; and may be divided into many different classes with regard to flame, caking and coking qualities. They are very easy to ignite, brittle and dull fracture, crumbly, and soil the fingers in handling, due to softness.

117. Coke is the resulting fixed carbon and ash which remains a porous mass after driving off the volatile matter from a bituminous or semi-bituminous coal. It is largely a product of the coal gas industry; but as a power station fuel, its price is practically prohibitory. Oven coke, which is very hard, is used for blast furnace and crucible furnace work.

118. Lignite is a more recent formation than the bituminous coals and is hardly distinguishable from the lower grades of these; it is non-fibrous, and often brownish in appearance, whereas the coals are all black; absorbs oxygen and gives off CO_2 at ordinary temperatures. It contains quantities of oxygen and the volatile matter given off is mainly CO_2, which distinguishes the lignites still further from the coals, whose volatiles are chiefly hydrocarbons.

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Sample	Bed	Proximate analysis				Ultimate analysis						Calorific value B.t.u.	
		Moisture	Volatile matter	Fixed carbon	Ash	Sulphur	Hydrogen	Carbon	Nitrogen	Oxygen	Air drying loss per cent.		
Alabama.....	Warrior field.....	2.58	33.15	51.74	12.53	1.02	4.79	69.24	1.55	10.87	0.8	12,449	Lump, Nut & Pea Coal
Arkansas.....	Huntington bed...	0.80	19.75	67.65	11.8	1.3	4.07	76.37	1.55	4.91	0.8	13,655	Lump & Slack.
Colorado.. ..	Boulder field.....	13.49	37.11	43.03	6.37	0.58	5.75	61.13	1.22	24.95	6.0	10,791	Run of Mine, Lignite.
California....	Alameda Co.....	18.51	35.33	30.67	15.49	3.05	5.93	47.34	0.66	27.53	10.4	8,500	Run of Mine, Lignite.
Illinois.....	Belleville field.....	5.31	34.29	36.24	24.10	4.3	4.57	54.06	0.78	12.13	7.1	9,848	Slack.
	Marion Co.....	5.96	30.29	52.16	11.59	1.77	4.92	67.30	1.43	12.99	2.7	12,103	Run of Mine.
	Montgomery Co...	13.2	34.33	39.94	12.53	4.47	5.51	57.25	1.02	19.22	4.4	10,514	Nut Coal.
	Franklin Co.....	8.31	31.65	49.56	10.43	1.55	5.18	65.83	1.48	15.48	4.6	11,727	Egg Coal.
Indiana.....	Warrick Co.....	6.24	37.49	42.76	13.51	4.6	5.11	62.97	1.25	12.56	3.6	11,538	Run of Mine.
	Sullivan Co.....	13.99	29.4	42.29	14.32	2.31	5.36	57.18	1.11	19.72	10.8	10,318	Run of Mine.
	Vigo Co.....	9.55	36.19	43.65	10.61	3.72	5.49	64.08	1.08	15.02	4.6	11,759	Lump Coal.
Indian Territory.	Hartshorne bed....	1.7	37.19	49.79	11.32	1.56	5.00	71.9	1.72	8.91	2.8	12,969	Run of Mine.
	McAlester bed.....	4.91	37.79	43.9	13.4	4.02	4.84	63.21	1.38	13.15	1.4	11,389	Lump Coal.
Iowa.....	Polk Co.....	4.52	40.96	38.99	15.53	6.83	4.93	60.62	0 93	11.16	9.8	11,356	Lump Coal.
	Lucas Co.....	9.22	32.71	44.52	13.55	3.42	5.35	59.89	1.22	16.57	6.8	10,989	Run of Mine.
Kentucky....	Western field.....	5.85	36.9	46.96	10.29	....	5.27	66 75	1.43	12.66	2.2	12,292	Run of Mine.
	High Splint bed...	4.36	35.02	56.92	3.7	0.67	5.16	77.44	1.57	11.46	2.8	13,923	Run of Mine.
Maryland....	Garrett Co.....	2.33	16.11	68.43	13.13	1.49	3.99	7 .21	1.29	4.89	1.4	13,255	Run of Mine.
Missouri.....	Rich Hill field.....	3.5	35.35	40.77	20.38	5.35	4.64	60.00	0.99	8.46	5.0	11,144	Run of Mine.
	Bevier field.....	9.14	34.53	39.02	17.31	5.3	4.96	56.25	0.99	15.19	2.6	10,451	Run of Mine.
Montana.....	Red Lodge.....	9.05	36.7	43.03	11.22	1.76	5.25	60.41	1.36	20.0	2.2	10,777	Black lig., washed nut
New Mexico..	Gallup field	10.86	35.14	46.9	7.10	0.64	5.73	64.34	1.05	21.14	1.6	11,435	Lump and Slack.
North Dakota	McLean Co.	35.96	31.92	24.37	7.75	1.15	6.54	41.43	1.21	41.92	12.7	7,069	Lump, Brown lig.
Ohio.....	Jefferson Co.	3.53	37.45	49.9	9.12	3.47	5.15	71.66	1.31	9.29	1.4	13,072	Lump, over ¾" screen.
	Guernsey Co.	6.65	33.94	48.86	10.55	3.13	5.3	67.38	1.2	12.44	2.6	12,179	Lump, over 1¼" screen.
Texas.....	Houston Co.	13.4	42.75	29.00	14.58	1.04	5.57	52.06	0.95	25.53	24.6	9,385	Brown Lignite.



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120. Properties of Mineral Oils

No.	Name and source	Density			Ultimate analysis				Prox. H_2O	B.t.u. per pound		
		Sp. gr.	F	Bé	C	O+N	H	S		By calorimeter	High value	Low value
1	Ogaio, crude	0.985	32	12.135	87.1	10.4	2.5	.....	.....	18,146	18,983	18,065
2	California, fuel	0.966	60	14.93	81.52	11.61	6.92	0.55	.....	18,667	18,926	17,903
3	California, Whittier	0.9637	60	15.28	.....	.....	.....	0.845	8.71	18,518	.....	.....
4	California and Bakersfield fuel	0.962	60	15.53	84.43	10.99	3.99	0.59	.....	.....	18,976	18,005
5	California crude	0.9572	60	16.24	86.3	16.7	.....	0.8	.....	18,646	12,723	21,254
6	Hanover	0.955	32	16.505	86.2	11.4	2.4	.....	.....	.....	19,488	18,493
7	California crude	0.9533	60	16.85	85.75	11.3	.....	0.67	.....	18,797	19,356	18,363
8	California, Whittier and Los Angeles	0.953	60	16.9	.....	.....	.....	0.98	4.93	18,714	.....	.....
9	Texas fuel	0.945	....	18.155	.....	.....	.....	.....	.....	19,242	.....	.....
10	California	0.943	60	18.47	.....	.....	.....	0.735	1.06	18,677	.....	.....
11	California, Whittier	0.9417	60	18.67	.....	.....	.....	0.975	1.06	18,626	.....	.....
12	Baku Russia heavy	0.939	60	19.26	86.6	12.3	1.1	.....	.....	19,440	20,052	18,978
13	Petroleum residue, Baku	0.928	....	20.95	87.1	11.7	1.2	.....	.....	19,260	19,761	18,739
14	Texas, Beaumont fuel	0.926	60	21.25	83.26	12.41	3.83	0.5	.....	.....	19,654	18,570
15	California	0.920	60	22.17	84.0	12.7	1.2	.....	.....	.....	19,917	18,807
16	Pennsylvania	0.914	70	23.18	86.1	13.9	.....	0.06	.....	.....	20,949	19,735
17	Shale oil, Ardeche	0.911	....	23.682	80.3	11.5	8.2	.....	.....	16,283	18,452	17,647
18	Ohio distillate	0.887	60	27.84	84.2	13.1	2.7	.....	.....	18,718	20,188	19,044
19	Pennsylvania, crude, heavy	0.886	32	28.01	84.9	13.7	1.4	.....	.....	19,210	20,654	19,457
20	Russian, crude, light	0.884	32	28.38	86.3	13.6	0.1	.....	.....	22,628	20,796	19,608
21	Shale oil	0.875	....	30.005	.....	.....	.....	.....	.....	18,217	.....	.....
22	West Virginia, heavy	0.873	60	30.37	83.5	13.3	3.2	.....	.....	.....	20,207	19,046
23	East Galicia	0.870	32	30.92	82.2	12.7	5.7	.....	.....	18,153	19,675	18,545
24	Kansas, crude	0.866	60	31.67	85.4	13.07	.....	.....	.....	.....	20,345	19,203
25	West Virginia, light	0.8412	....	36.435	84.3	14.1	1.6	.....	.....	18,502	20,809	19,578
26	Ohio distillate	0.838	60	37.07	.....	.....	.....	.....	.....	19,880	.....	.....
27	Ohio, Mabery Noble	0.829	70	38.89	85.0	13.8	0.6	0.6	.....	.....	20,752	19,547
28	Pennsylvania, crude	0.826	60	39.50	82.0	14.8	3.2	.....	.....	17,930	20,699	19,606
29	American petroleum	0.82	....	40.73	83.4	14.7	1.9	.....	.....	17,588	20,042	19,758
30	Pennsylvania, light	0.816	....	41.57	82.0	14.8	3.2	.....	.....	17,533	19,899	19,606
31	American, crude	.....	.....	.....	83.0	14.4	3.0	.....	.....	19,980	20,801	19,544
32	Caucasus, Russia	.....	60	.....	84.94	13.96	1.25	.....	.....	18,610	20,817	19,649

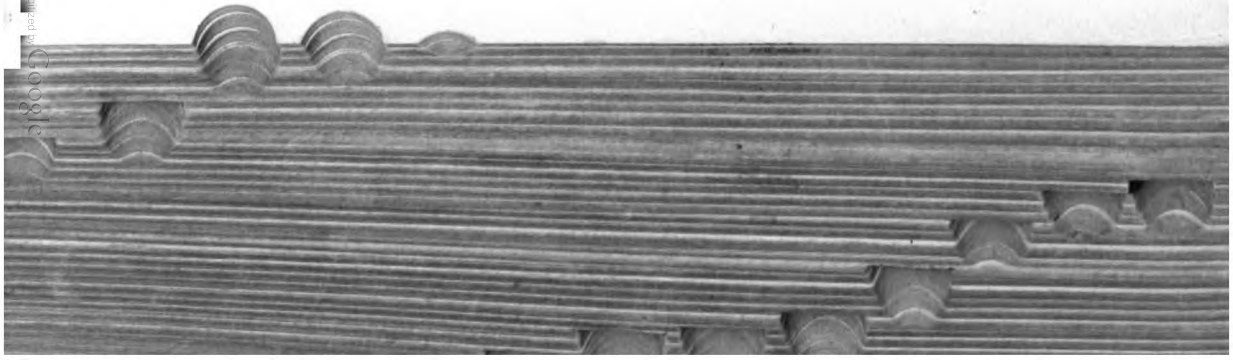
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121. Composition of Natural Gases (volumetric)

No.	Source	Authority	O_2	CH_4	C_2H_6	H	CO	C_2H_4	N_2	CO_2
1	West Virginia	Report Gas Eng. Com. N.E.L.A.	0.4	99.5	0.1	.....	.....	.....	.....	.....
2	Kansas	Report Gas Eng. Com. N.E.L.A.	0.25	98.3	.....	.....	0.25	.....	1.2	.....
3	Kokomo, Ind.	Levin	0.3	94.16	.....	1.7	0.55	0.3	2.8	0.29
4	Marion, Ind.	*Eng. & M. J.*	0.55	93.57	.....	1.2	0.6	0.15	3.42	0.3
5	English	Lewes	.....	93.16	2.94	.....	1.0	.....	2.9	.....
6	Anderson, Ind.	*Eng. & M. J.*	0.42	93.07	.....	1.86	0.73	0.47	3.02	0.26
7	Ohio	Lewes	0.35	92.84	0.35	1.89	.....	.....	3.82	0.75
8	Leechburg, Pa.	Hoyle	.....	89.65	.....	4.79	0.26	4.39	.....	0.35
9	West Virginia	Report Gas Eng. Com. N.E.L.A	0.15	81.5	17.6	0.2	.....	.....	0.55	.....
10	Butler County, Pa.	Hoyle	.....	80.11	.....	13.5	.....	5.72	.....	0.66
11	Penna.	Jüptner	.....	67.0	5.0	22.0	0.6	1.0	3.0	0.6
12	Pittsburgh, Pa.	Hoyle	0.8	67.0	.....	22.0	0.6	5.0	3.0	0.6

122. Composition of Coke Oven and Retort Coal Gas (volumetric)

No.	Description	H_2	CH_4	CO	C_2H_4	C_6H_6	Heavy hydrocarbons	CO_2	O_2	Remainder and N_2
1	Solvay coke oven	56.9	22.6	8.7	.....	.....	3.0	3.0	.....	5.8
2	Coke-oven gas	53.0	35.0	6.00	2.0	.....	.....	2.0	.....	2.0
3	Retort coal gas, Lewes, 6.5–7.5 O in coal	52.79	34.43	7.19	3.02	.99	.....	1.58	.....	.....
4	Retort coal gas, Newton, Mass.	50.59	34.80	6.16	.....	.....	5.23	1.16	.....	2.06
5	Laclede Gas Co., bit. coal	49.8	32.3	6.7	.....	.....	8.0	2.40	.60	0.2
6	†Good Solvay average coke-oven gas	48.0	35.5	5.1	4.2	1.2	.....	1.3	.5	4.2
7	Common coal gas	47.73	35.6	6.15	4.88	.....	.....	1.41	.31	3.92
8	Coke oven, Milwaukee	47.1	34.7	6.2	3.8	.....	.....	3.1	.3	4.8
9	Sheffield retort gas, cannel	43.05	43.05	4.72	.....	.....	6.28	.24	.10	2.56
10	Otto coke oven, poor part of gas	41.6	29.6	6.3	.....	.....	2.8	3.2	.4	16.1
11	Birmingham, Eng., retort coal gas	40.23	39.0	1.50	.....	.....	4.76	1.50	.....	13.01
12	Otto coke oven, good part of gas	37.6	40.8	5.6	.....	.....	5.8	3.7	.4	6.1
13	Cleveland, Ohio, retort coal gas	34.8	28.8	.20	.....	.....	11.2	.20	.....	24.8
	High volatile coal:									
14	Solvay oven, Blauvelt, 6th hr	49.8	31.4	4.6	1.6	.90	.....	1.1	1.1	9.5





123. Composition of Blast-furnace Gas and Air Gas

No.	Description	Volumetric analysis						
		CO	H_2	CH_4	CO_2	N_2	$\frac{CO}{CO_2}$	$\frac{CO}{CO+CO_2}$
1	Coke in small Dowson producer, Dowson and Larter	32.6	1.0	.....	1.4	65.0	23.2	.96
2	Metallurgical air gas, Lewes	29.0	2.5	.....	4.0	64.5	7.25	.88
3	Coke, Lackawanna Steel Co	28.4	1.7	.....	11.8	.....	2.40	.71
4	Blast furnace, splint coal, Sexton No. 2	28.06	5.45	4.39	8.61	53.38	3.26	.76
5	Blast furnace, English	27.71	1.34	.....	8.62	62.33 +5.0	3.21	.76
6	Blast-furnace gas	27.5	3.0	.....	10.0	59.4	2.75	.73
7	Bituminous coke air gas, Loomis Pettibone	27.3	5.1	.8	2.7	.....	10.1	.91
8	Coke Lackawanna Steel Co	26.8	1.4	.....	8.6	.....	3.12	.76
9	Isabella Furnace, U. S. Steel Co., Gayley	25.8	.....	.....	12.6	4.25	2.04	.67
10	Producer gas, little steam	25.3	9.2	3.1	3.4	58.2	7.44	.88
11	Dowson gas, average	25.0	18.0	3.0	7.0	47	3.57	.78
12	Producer gas, little steam	24.8	8.5	5.2	5.6	55.1	4.44	.82
13	Producer gas, little steam	24.0	9.8	3.4	6.0	55.6	4.0	.80
14	Blast-furnace coke	24.0	2.0	2.0	12.0	60.0	2.0	.67
15	Blast furnace, Ledebur, Germany, coke, of 10 per cent. H_2O	21.6	1.8	1.8	10.8	54.0 +10.0	2.0	.67
16	Producer gas, little steam	20.0	5.3	3.0	3.6	67.5	5.56	.85
17	Loomis Pettibone coal	20.0	14.0	2.0	8.2	55.5	2.44	.71
18	Taylor gas, average	12.0	21.0	2.0	5	57.0	2.4	.71
19	Mond gas	12.0	29.0	2.0	14.5	42.5	.83	.45
20	Mond gas	11.5	28.5	2.1	15.0	42.9 water	.77	.43

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124. Peat is the most recent of the formations. High-bog peat is formed from swamp moss, etc.; low-bog peat is formed from grasses around low bodies of water. They show the fibrous structure of vegetable origin, and range in color from ochre to brown and black; are very soft in texture, with no fracture; carry large moisture, oxygen and nitrogen content; the volatile matter is poorly combustible, containing largely CO_2.

125. Wood is still higher in oxygen and nitrogen, up to 40 to 45 per cent., with carbon from 45 to 49 per cent. Its scarcity and cost make its use as a power station fuel impossible except for saw mills and logging camps where the unmarketable waste may be profitably used.

126. Briquettes* are small artificial lumps of solid fuel made up by pressing peat, bituminous slack or anthracite culm, with a suitable tarry binder, so as to recombine the soft peat or unmanageable coal dust into a convenient lump form. Briquettes behave somewhat like lumps of soft coal, but usually are very troublesome in giving smoke. The cost of briquetting presses, and the need of suitable inexpensive binder, have prevented the wide use of briquettes in America. With peat briquetting is practically a necessity.

127. Mineral oils have their source in crude petroleum. The heavy oil engines, such as the Diesel and the Junkers run on raw petroleum; many of the smaller engines, however, are designed for kerosene and gasolene.

128. Gas for power production may be natural gas,† producer gas, coke-oven gas,‡ or blast-furnace gas.§ Illuminating gas is too expensive to use for anything but very small isolated plants. See Par. 121, 122 and 123.

129. The main feature in the use of gas is the engine compression pressure which is practicable; blast-furnace gas, being lean and much diluted with neutral matter, will stand very high compression; producer gas, natural and coke-oven gas, being richer (especially in hydrogen), cannot be compressed as much.

130. The cost of anthracite No. 1, No. 2, or No. 3 buckwheat is about \$2.50 to \$6.00 per ton at the plant in quantity. The mine cost is not over \$2.00 to \$3.00. **Bituminous coal** costs from \$5.50 to \$9.00 at the plant. The cost averages \$0.17 to \$0.19 per million B.t.u. (1921).

131. Fuel oil costs from \$0.025 to \$0.07 per gal. The cost averages about \$0.18 to \$0.20 per million B.t.u., in the oil-burning districts. While its cost per million B.t.u. is about the same as coal, or somewhat better, in the districts where it is available, it has a further advantage in the better boiler efficiency obtained, and in the elimination of some of the power-station auxiliary apparatus (1920–21).

132. Natural gas costs \$00.13 to \$0.16 per million B.t.u. All of these figures apply chiefly to large consumers; the prices will go up considerably for small plants.

WATER SUPPLY AND PURIFICATION

133. Boiler feed. Boilers must be fed with fresh water of reasonable quality; in general, if a water is not potable, it is not fit, as it stands, for boiler feed. Wells, fresh-water lakes, rivers and ponds are the prime sources.

134. Water analysis to determine the value of a water as boiler feed should be performed by a chemist; but the ordinary tests for hardness, with standard soap solution, hydrochloric acid and methylorange, may readily be carried out in the plant in conjunction with water-softening apparatus.

135. The dangerous impurities are sulphuric acid (or other acids if the water has been contaminated by factories), grease and oils in quantity,

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*Lucke, C. E., "Engineering Thermodynamics." McGraw-Hill Book Co., Inc., New York, 1913; Table CIV.

†Lucke, C. E., "Engineering Thermodynamics." McGraw-Hill Book Co., Inc., New York, 1913, Table CIX.

‡Lucke, C. E., "Engineering Thermodynamics." McGraw-Hill Book Co., Inc., New York, 1913, Table CX.

§Lucke, C. E., "Engineering Thermodynamics." McGraw-Hill Book Co., Inc., New York, 1913, Table CXIV.

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and the natural scale-forming salts such as magnesium, iron and calcium carbonates and sulphates.

136. The treatment of feed water has been outlined in Par. 49 to 51.

137. The use of condensate returned from surface condensers is usually a valuable way of eliminating most of the boiler incrustation. The only drawback lies in the presence of oil and grease in the condensate, if the condenser serves a reciprocating engine. Quantities of oil in excess of 0.4 to 0.5 g. per gal. are objectionable, as they collect whatever soft scale may be present in the boiler and form a brown mass which bakes on the tubes and has the same effect as hard scale.

138. Oil and grease extractors, designed on the same general lines as steam separators are employed between the engine and condenser, in order to keep down the amount of oil passing into the condensate. As a matter of fact, the baffles placed in these devices are really of very little use; it is the reservoir effect of the extractor in slowing down the current of steam which really does the work. Where turbines are the prime movers, no grease or oil separators are required. Fig. 20a shows a typical separator.

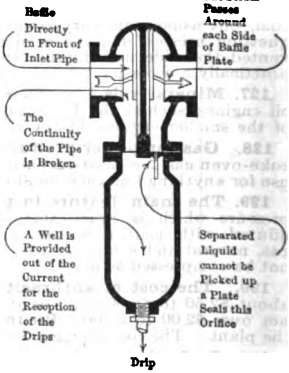


FIG. 20a.—Horizontal steam separator.

COAL AND ASH HANDLING

139. Coal is delivered to the power plant of any size, either by barge, schooner or railroad car. Handling coal by truck is practically too expensive for use in any but small isolated plants.

140. Unloading may be done by a grab-bucket digger, or if delivered by car, an elevated trestle may be employed, dumping from the car bottoms. For most of the large plants, a coal tower with a 1-ton or 1.5-ton clam-shell digger is employed to unload and hoist the coal high enough to pass by gravity through crushers and weighing scales, and finally to conveyors or coal cars. In smaller plants, a locomotive crane, or monorail telpher, may perform the same work and also serve the storage yard. Towers may be either steam or electric driven; the former is generally the cheaper and more rugged construction.

141. Crushers are heavy rolls of cast iron, studded with teeth, geared together in such fashion as to crush the coal to small size; some spring or relief device must be fitted to allow harder materials to pass through, such as link chains, sprags and occasionally a car coupler. Crushers are not needed for anthracite.

142. Conveyors are of five principal types; scraper, reciprocating, belt, bucket and suction. **The scraper conveyor** consists of flights or paddles rigidly fastened upon a special bar-link chain, and dragged along in a trough shaped to the flights. The **reciprocating conveyor** is very similar, but only moves a few feet forward and backward. The flights are so hinged that on the backward stroke they lift out of the coal and trail over the top, digging in again when the chain reverses.

143. Belt conveyors consist of wide rubber or textile belts travelling continuously over idlers spaced from 2 ft. to 4 ft. apart, and with the outer pulleys tilted up to trough the belt. The belt conveyor is not suitable for hot ashes.

144. The bucket conveyor has separate buckets from 24 in. to 48 in. square, either fixed rigidly to long-pitch side links, or pivoted in the center, so as to remain vertical. In the latter case, all of the conveyor is malleable iron except the rails and framing. It is exceptionally suited to handling ashes.

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145. The suction conveyors are used only for **ashes**; coal is too heavy and packs too readily to be handled in this manner. The suction is usually provided by a high-speed centrifugal blower, attached to the outlet, or a steam jet eductor. The rest of the equipment consists merely of 6-in. to 12-in. cast-iron pipe lines with swing-door openings at which the ashes are admitted. The drawback to this system is the deterioration of the fan from grit, and all turns and elbows from abrasion. If the ashes are too wet, the blocking of the pipes is practically certain to give trouble.

146. Comparisons of conveyors. The belt conveyor is very satisfactory on "carry" of coal, but not so good on "lift;" the bucket conveyor is probably the most satisfactory all-around conveyor, handling coal or hot ashes equally well in lift or carry; it is, however, the most expensive. The steam jet conveyor has been successful chiefly in small or moderate size plants.

147. Another method of conveying is by cable cars; where possible this gives the cheapest and most satisfactory means of carry.

148. Storage of coal outdoors for power-plant purposes requires less care and handling than for coal companies, as the material is turned over fast enough to avoid much loss by weathering. The storage yard may be served by: (*a*) a locomotive crane, (*b*) a gantry crane, (*c*) a Dodge girder unloader, (*d*) a telpher grab bucket operating on an overhead structure, (*e*) or if the storage is in a pit, by a conveyor in a tunnel. Usually the capacity should equal at least two weeks supply, or better, one month. One company having trouble from spontaneous combustion of bituminous coal, uses a concrete pit flooded with water; but this is generally unnecessary, the excessive wetting of the coal being a drawback.

149. Bunkers placed under the roof of the boiler house are almost always provided, to feed coal by gravity to the fires. Where external storage is available, two to four days supply in the building is all that is necessary; but in city plants where external storage is impossible, ten days to two weeks supply must be provided.

150. Bunker construction. Steel framing with concrete or cinder-concrete lining, faced with granolithic or other hard finish, is the best construction for large work; for smaller work, the suspended type, catenary shape, of plate steel with concrete lining, or simply of reinforced concrete, has been much used.

151. Hoppers. Ash hoppers of structural material with brick lining are the standard practice, but reinforced concrete is also being used to some extent. The coal hoppers should always be of sheet steel, $\frac{3}{8}$ in. being the usual thickness; it is good practice to reinforce the hoppers with renewable wearing plates where the abrasion is severest.

152. Weighing is done at the hoisting tower (just after crushing) in hoppers carried in knife-edge supports which operate standard beam scales; two sets are required, one hopper receiving the continuous flow of coal from the crusher while the other is being weighed. Reversing gates for the supply, and trip gates for the weighing hoppers are under the control of the weighmaster.

153. Automatic scales of the hopper type are in use for anthracite, and are fairly accurate, as the angle of repose and slip of anthracite in the small sizes is very little affected by moisture, and the small size allows ready control of the flow; with bituminous coals they are somewhat less accurate over short runs, as the highly variable angle of repose affects the spillage when closing the feeder gates, making the "dribble" a variable quantity: but over longer periods, say a month, the error averages and they work very well. Conveyor scales of several makes are on the market, but not widely used.

154. There is also a coal meter for use in pipe downtakes, acting on the principle of a propeller driven by the moving coal, which is very simple and quite accurate for small sizes of coal. It is not yet fully satisfactory for lump coal and run of mine.

155. Spouting of coal in closed pipes must always be done at an angle of 45 deg. or steeper to be satisfactory, if the spout is a closed pipe; 8-in. to 10-in. pipes may be used with anthracite; but nothing less than 12 in. should be used for bituminous crushed coal. In designing hoppers and spouts it should be remembered that the intersection of two sides each at 45 deg. from the horizontal, is much less than 45 deg., so that the coal will always hang at such a junction.

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156. The power required by belt conveyors is given by the following formula:

$$H.P. = \frac{CTL}{1{,}000} + \frac{TH}{1{,}000} \qquad (26)$$

where C = power constant, T = load in tons per hour, L = length of conveyor in feet, H = lift of conveyor in feet, and B = width in inches.

Values of C for material weighing 25 lb. to 75 lb. per cu. ft.

B (in.)	C	H.P. on account of trippers in belt	B (in.)	C	H.P. on account of trippers in belt
12	0.234	0.5	26	0.187	2.0
14	0.226	0.5	28	0.175	2.25
16	0.220	0.75	30	0.167	2.5
18	0.209	1.0	32	0.163	2.75
20	0.205	1.25			
22	0.199	1.5	34	0.161	3.0
24	0.195	1.75	36	0.157	3.25

Add 20 per cent. for conveyors under 50 ft. long.

Add 10 per cent. for conveyors between 50 and 100 ft. long.

The formula does not include friction of gear drive. Add about 10 per cent. for the drive and 10 per cent. for each 180 deg. turn idler, exclusive of the head and tail pulleys. Speeds run from 300 to 450 ft. per min.

157. The power required by flight or scraper conveyors is as follows:

$$H.P. = \frac{ATL - BWS}{1{,}000} \qquad (27)$$

where A and B are constants in the table below, W = weight of chain and flights in both runs, L = length of feet, S = speed in feet per minute, and T = load in tons per hour.

Values of A and B

Inclination	0 deg. or horizontal	5 deg.	10 deg.	15 deg.	20 deg.	25 deg.	30 deg.	35 deg.	40 deg.	45 deg.
A.....	0.343	0.42	0.50	0.585	0.66	0.73	0.79	0.85	0.90	0.945
B.....	0.01	0.01	0.01	0.01	0.009	0.009	0.009	0.008	0.008	0.007

Speeds 100 to 200 ft. per min.

158. Bucket Elevators and Conveyors

Size, buckets,	12″×12″			24″×15″			36″×20″			48″×24″		
Spacing.....	18″	24″	36″	18″	24″	36″	18″	24″	36″	48″		
H.p. for 100′ vertical lift.....	0.46	0.35	0.23	1.35	1.0	0.67	3.8	1.9	3.5	2.7		
H.p. for 100′ horizontal run empty	1.2	1.1	0.9	1.7	1.5	1.3	2.4	1.6				
H.p. for 100′ horizontal run full, anthracite.....	2.5	2.1	1.5	5.3	4.3	3.1	12.4	6.6				
H.p. for 100′ horizontal run full, bituminous coal.	3.2	2.6	1.9	7.4	5.8	4.2	18.0	9.4				

Add 5 per cent. for each turn.

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159. **Ash handling** is very frequently done by trolley locomotive and side dump cars, in large plants; these allow for thorough quenching before delivering to conveyors for elevation. Of the conveyors, the malleable-bucket type lasts the best in ash service. A skip hoist may be substituted for conveyors, for elevation; and where it can be used, is a most satisfactory means of disposal. Ash bunkers are almost always provided for storage purposes, as in many plants the ash removal from the individual boiler ash hoppers is done on night shift, when cars or boats are not readily available.

160. **Helical or screw conveyors.** The power required is

$$H.P. = \frac{W'LC}{33{,}000} \tag{28}$$

where W' = capacity in lb. per min., L = length in feet and C = 0.67 for coal, 1.00 for ashes.

161. **Typical combinations** are: low-hoist grab-bucket tower, containing crusher and scales; belt conveyors, horizontal, to power station; V-bucket or pivoted-bucket elevator, belt distribution at top of building to bunkers. Inclined belts may be used for "lift," but are not too satisfactory. Belts are very good on "carry," however. If the tower is close to the building, bucket elevators may be used both for lift and carry. A very good arrangement is: high towers, performing the whole lift at once, delivery through crusher and scales to cable car for distribution over bunkers. For small or moderate size plants telpher grab buckets offer a satisfactory solution, serving storage yard, cars or boats, and bunkers on overhead monorail structure. The usual system for ash disposal consists of collection from ash hoppers by industrial railway and trolley locomotive, and delivery to skip hoist or bucket elevator for lifting to ash storage pockets, for which the ashes are spouted to cars or barges. The vacuum system is useful for small and moderate size plants; or a single hand car may be enough. Belt conveyors should never be employed for ash handling.

162. **The cost of conveyors** is exceedingly variable and is dictated chiefly by structural conditions. It is almost impossible, therefore, to give unit costs. Belt conveyors of the lengths usual in power station work cost from \$2.00 to \$3.00 per inch of belt width, per foot of conveyor; bucket elevators and conveyors, roughly \$0.40 to \$0.50 per ton capacity per hour, per foot of conveyor.

STEAM ENGINES

163. **Source of energy.** The steam engine must obtain its energy from the heat drop available by adiabatic expansion between any two pressures. For adiabatic expansion, there must be no heat interchange with the surroundings while the mass of steam in the cylinder undergoes the expansion; therefore a non-conducting cylinder is required. This is commercially unattainable, and consequently the expansion is never truly adiabatic. The heat drop obtainable is always less, if the expansion is not adiabatic.

164. **The thermal efficiency of a perfect engine** working on the Rankine cycle (Par. 166) is given as

$$E_r = \frac{H_1 - H_2}{H_1 - h_2} \tag{29}$$

where H_1 = total heat of steam at initial condition (pressure and quality or superheat), H_2 = total heat of steam at final pressure after an adiabatic expansion (constant entropy), and h_2 = heat of the liquid, at final pressure. For modern steam pressures, superheats and vacua, this possible efficiency does not exceed 40 per cent. for turbines. The usual steam pressures and vacuum for reciprocating engines would not give a higher efficiency than 30 per cent.

165. **The efficiency ratio** for good compound engines seldom reaches 60 per cent., giving an actual thermal efficiency of 18 per cent., 13 per cent. and 14 per cent. are more commonly reached in large size reciprocating engines.

166. **The Rankine cycle** upon which these comparisons are based pre-supposes a non-conducting cylinder, no leakage and no clearance; admission at constant pressure, instantaneous cut-off; expansion adiabatically to the back pressure; exhaust at constant pressure; and since there

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is no clearance, no compression is required. In the real engine, conduction of heat, leakage, wire-drawing, friction, incomplete expansion, and clearance all tend to reduce the efficiency ratio by adding losses.

167. A single-expansion engine is one in which the complete expansion from initial to back pressure takes place in one cylinder; a **compound engine** is one in which the expansion is from the initial pressure to an intermediate pressure in one cylinder, and from this intermediate pressure to the back pressure in a second cylinder. A **triple or quadruple expansion engine** performs the expansion similarly in three or four stages, respectively. All engines using more than one cylinder to complete the expansion are termed **multiple expansion**, in general.

168. Cut-off usually takes place at ¼ to ½ stroke in simple non-condensing engines, ½ to ¾ in condensing. **The number of expansions** is the ratio of final cylinder volume to volume contained at cut-off; for simple non-condensing engines the ratio is 3 to 4; simple condensing, 5 to 8; compound and triple, etc., 8 to about 50. For power station purposes 16 to 20 is common, with compound condensing units.

169. Non-condensing engines exhaust freely to atmosphere, or to a system in which the pressure is atmospheric or a few lb. per sq. in. above; condensing engines exhaust to a condenser in which a partial vacuum is maintained, below atmospheric pressure.

170. High-speed engines operate at 350 to 250 rev. per. min., in sizes from 5 h.p. to 500 h.p. **Medium-speed** engines operate at 250 to 150 rev. per min. in sizes from 250 h.p. to 1,000 h.p. **Low speed** engines (generally Corliss types) operate from 100 to 70 rev. per min., in sizes from 400 h.p. to 8,000 h.p.

171. Single-acting engines take steam on one side of the piston only; they may be simple, compound or triple expansion; and are always high-speed engines, usually with vertical cylinders.

172. The slide valve in the original D-valve form is unbalanced, moving on flat faces; it is unsuitable for large sizes and heavy pressure. Balanced forms of the slide valve, such as the Ball, Skinner, Mackintosh & Seymour grid, etc., overcome some of these objections. **The piston valve**, shaped like a piston, is inherently balanced; it can be made tight, but requires large clearance percentage, on account of length of the ports.

173. The Corliss valve is of general cylindrical shape, oscillating over ports parallel to the axis of the valve and crosswise of the cylinder; it can take care of but one function, therefore four are required per cylinder, two for admission and two for exhaust. The preceding types, except the grid, take care of all four functions with one valve. The Corliss valve is always used with a trip or releasing gear to vary the cut-off without changing any other event in the steam admission or exhaust. In all fixed valve gears, it is usually impossible to vary the cut-off without varying other functions at the same time.

174. Poppet valves are those in familiar use on automobile engines; but for steam use are generally made double-seated so as to be balanced. They have met with great success in Germany, and are undoubtedly the best type for superheat. They may be used with releasing gears, and require four valves per cylinder, as with the Corliss type.

175. Jackets for keeping the cylinder hot with live steam, to reduce condensation in the cylinder, have been used with some success for pumping engines; but have not been successful in many other applications.

176. Receivers are used to eliminate variations of pressure between high-pressure and low-pressure cylinders in multiple-expansion engines, due to intermittent exhaust and admission: they must be of large capacity to be effective. **Reheating coils** are sometimes employed to dry the steam passing through these receivers, to improve conditions in the succeeding cylinders. They are of practically no value in engines for power-station service.

177. Governors for steam engines are of two principal types: flyball and shaft governors. The flyball type consists of two or more weights or balls supported by movable arms, the whole rotated around a shaft so that centrifugal force tends to throw the balls outward; this tendency is resisted by weights or springs, and the relative movement of the arms made to operate

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the engine valve gear. In the **shaft governor** the weights are arranged to rotate vertically around the main crank shaft, and attached direct to the eccentrics without the intervention of other mechanism. It cannot be used with slow-speed engines, nor with any form of trip or releasing gear. Inertia effects are introduced in the Rites type of shaft governor.

178. Either centrifugal or inertia types of governor can be made isochronous, but are generally only approximately so; isochronism, or complete instability of the governor at all speeds except the correct speed, is undesirable, causing hunting.

179. Engine frames are usually made entirely of cast iron, for stationary work; the vertical engines are of the A-frame type in large and small sizes and of the enclosed type, with automatic oiling, for small and moderate size, only. Horizontal engines of small and moderate sizes, may be enclosed, with automatic or splash oiling.

180. Girder frames. The large horizontal Corliss type engines are made with girder frames connecting the cylinders and the main bearings, for the **standard type**; in the **heavy-duty type**, the girders are completely surrounded by the frame, which is carried down to the sole plate all the way from cylinder to main bearing.

181. Mean effective pressure is the average pressure which if exerted during the full stroke would equal the work done by the varying pressures really existing during the course of the stroke. The mean effective pressure (m.e.p.) is obtained from the indicator card as follows:

$$\text{M.e.p. in lb. per sq. in.} = \frac{\text{card area in sq. in.} \times \text{scale of spring}}{\text{card length in inches}} \qquad (30)$$

The shorter the cut-off, the lower the m.e.p. for any given steam pressure and back pressure; consequently the larger the cylinder dimensions become for a given horse-power, other things being constant.

182. Cylinders are usually so proportioned as to divide the total work equally between high- and low-pressure cylinders; roughly, for compound engines, the cylinder ratio is given by

$$Rc = \left(\frac{P_1}{P_3}\right)^{\frac{1}{2}} \text{ and } P_2 = (P_1 P_3)^{\frac{1}{2}} \qquad (31)$$

where Rc = cylinder ratio, or ratio of low-pressure displacement to high-pressure displacement, P_1 = initial pressure in lb. per sq. in. absolute, P_2 = receiver pressure in lb. per sq. in. absolute, and P_3 = back pressure in lb. per sq. in. absolute.

This is based on no clearance, no compression, equal cut-off in both cylinders, logarithmic expansion, and receivers of infinite capacity. It is varied in practice by the clearance of both cylinders; by finite receivers and by the effects of wire-drawing.

183. The speeds usually employed in America are given in Par. **170**. Snell gives a table of usual English practice, which is slightly higher than American usage.*

For sizes above 1,750 k.w., the speed is from 75 to 60 rev. per min., for Corliss engines. **Piston speeds** range from 350 to 600 ft. per min. in the high-speed engines, and from 600 to 750 ft. per min. in the low-speed, long-stroke Corliss types.

184. Indicated horse-power is given by the indicator, and is the amount of power actually developed in the cylinder by the steam. **Brake horse-power is the actual output at the shaft.**

$$\text{I h.p.} = \frac{PLAN}{33{,}000} \qquad (32)$$

where

P = mean effective pressure, lb. per sq. in.;
L = length of stroke, ft.;
A = piston area, sq. in.;
N = number of strokes per min.

* Snell, "Power House Design," p. 146, Table XLVII.

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185. The mechanical efficiency is given by the formula

$$E_m = \frac{\text{b.h.p.}}{\text{i.h.p.}} \tag{33}$$

where E_m = mechanical efficiency, b.h.p. = brake horse-power, and i.h.p. = indicated horse-power.

$$\text{Friction h.p.} = \text{i.h.p.} - \text{b.h.p.} \tag{34}$$

Lucke gives the formula

$$E_m = 1 - \frac{K_1 - K_2}{(\text{m.e.p.})} \tag{35}$$

where $K_1 = 0.02$ to 0.05, average 0.04; and $K_2 = 1.3$ to 2.0, average 1.6.

186. Mechanical design of the steam engine is limited by first cost, efficiency and reliability: these three factors exert influences in varying directions. Low cost per h.p. capacity indicates high rotative speed and simplicity of mechanism. High economy indicates lower speeds, complicated valve gear, multiple cylinders, reheaters and large receivers. Reliability dictates heavily built parts, elimination of small parts, and especially the elimination of small bearings. **The outcome** is that for small powers, moderate speeds and low steam pressures, the simple non-condensing slide-valve engine, throttle governed, is used. Under steady load and speed it has fair economy, and is very reliable. For small electric isolated plant service, the high-speed automatic engine, with shaft governors and piston-valves or balanced slide valves, is used. For higher powers the low-speed condensing engine, either simple or compound, is adopted. The higher economy demanded justifies the increased cost due to low speed and Corliss valve gears; reliability is also provided, since the complex gear is now large enough not to be fragile.

187. Friction loss, which causes the difference between brake and indicated power, is made up of bearing friction; piston, valve and rod friction; and windage. The principal bearing friction occurs in the main bearings, crank pins and crosshead slippers, the remainder occurs in the valve gear. **Suitable lubrication** greatly reduces this kind of friction. Piston, valve and rod friction occur in a steam atmosphere where lubrication is at best uncertain. The latter depends upon the type of valve, whether balanced or not; upon the kind and number of piston rings; and upon the condition of the rod packing.

188. Lubrication of all bearings is accomplished with engine or machine oil; or prepared grease. In small engines, sight-feed oil cups are commonly used; for large units, a central gravity oiling system piped to all bearings is considered the best practice. In the latter case, the oil is caught after use and returned to filters, whence it is again pumped to the elevated supply tank. In this way copious supplies of oil may be given without great expense and the friction is very much reduced. **Splash oiling** in closed crank-case engines is employed for high speeds and small or moderate sizes. Grease can only be fed by individual compression cups at each bearing.

189. Cylinders are oiled with heavier lubricants, whose lubricating qualities in the steam become the same as ordinary engine oil at room temperatures. Cylinder oil is fed into the steam pipe just above the throttle, or into the steam chest: a hydrostatic sight-feed lubricator, or a force pump may be employed. The latter is considered the better method. **Graphite** has been used with much success in assisting cylinder lubrication; the chief difficulty lies in getting it into the cylinder.

190. The total losses occurring in a steam engine can be classified as follows: cylinder condensation; leakage; clearance; incomplete expansion; wire-drawing; radiation; mechanical friction.

191. Cylinder condensation is caused by the conduction of heat away from the steam through the cylinder walls; the cylinder assumes an average temperature about half-way between steam admission and exhaust temperatures. Consequently the hot in-coming steam gives up heat to the cooler walls; some of this is returned, too late to be of use, during the exhaust stroke. **Moisture in the entering steam** makes this effect worse; but **superheat** much improves it, by increasing the surface resistance to heat transmission.

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192. Leakage occurs past all sliding joints—the joint behaves like an elongated capillary orifice for steam flow; such joints occur at the piston, the piston rod, the valve seat and the valve rod. The means of reducing leakage are generally snap and spring-rings for pistons and piston valves, pressure plates insuring a close fit for flat balanced valves, and sectional metallic or soft packing compressed by a gland, for all rods.

193. Clearance is any space left between the valve and the piston, when the latter is at the end of the stroke. It varies from 3 to 4 per cent. of the displacement in well-designed Corliss engines; from 8 to 14 per cent. on high-speed and medium-speed engines; from 15 to 30 per cent. in badly designed or low-price slide-valve and piston-valve engines.

194. Zero clearance is not possible in any commercial construction, since piston must have some clearance from the cylinder head, and the steam and the exhaust passages must always have some volume. Clearance necessitates compression, in order to bring the volume of steam trapped in the clearance space to approximately the initial pressure; this has the double effect of cushioning the engine and avoiding loss due to filling the clearance space with fresh steam at each stroke.

195. Incomplete expansion is due to the limitations in size of cylinders, which commercially cannot be made large enough to handle the high volumes at low pressure.

196. Wire drawing is the term applied to pressure drop between steam chest and cylinder due to insufficient area in the valves and ports, or slow opening of the valve; it reduces the effective pressure and therefore causes a loss.

197. Radiation is the heat loss which occurs when the cylinder temperature is higher than that of the surrounding air. Not only the cylinder, but also those parts of the engine which become hot by conduction, radiate heat. The cylinder is heavily lagged (or even jacketed in a few cases) to reduce the loss. This loss amounts to 1 or 2 per cent. of the total heat of steam used by the engine.

198. Indicated horse-power is obtained from the indicator card (Par 184) and was the basis of most guarantees up to a few years ago. Brake horse-power, which is the useful power delivered at the shaft, is now more common.

199. Non-condensing single-cylinder engines are usually rated at ⅛ or ¼ cut-off and 100 lb. gage steam pressure; compound non-condensing engines at ⅛ to ¼ cut-off in the high-pressure cylinder and 150 lb. gage pressure; simple condensing engines at ⅛ or ¼ cut-off and 125 to 150 lb. gage pressure. The guarantees should always state steam pressures, back pressures and actual cut-off, instead of the above figures.

200. The locomobile type of engine developed abroad and lately introduced in this country is a combination consisting of a tandem compound engine mounted directly on an internally fired boiler. The high-pressure cylinder is in the smoke flue, and the low-pressure cylinder is jacketed by the steam dome. A superheater is also fitted in the smoke box. The advantage of maximum jacketing effect, high superheat, and practically no piping losses, make the fuel economy high. This type of unit is now manufactured in this country, but the advantages of the turbine, coupled with the comparative inflexibility of a single boiler-engine unit, will prevent extensive use of the locomobile in America.

201. Exhaust steam heating makes use of the heat wasted by the engine; it may amount to 80 or 90 per cent. of the heat originally in the steam. Consequently, the power is obtained at very low cost for fuel, since most of the ordinary inherent losses are recovered as heat in the heating system. Hence in many industrial plants serving buildings with lighting and power service, non-condensing engines are used. Generally the expense of a condenser to be used during the summer months will not be justified, as the small gain in economy for the year will not offset the fixed charges on the condenser equipment.

202. Average steam-engine performance is best represented by a combination of the efficiency ratio and heat drop available from the steam conditions existing, since the efficiency ratio is the least affected variable involved.

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The efficiency ratio is defined as the steam consumption of the Rankine cycle, divided by the actual steam consumption (per i.h.p.-hr., per brake h.p.-hr., or per kw.h., as the case may be); or, the ratio of the actual efficiency to the Rankine efficiency. The Rankine cycle efficiency is found as follows: on the Mollier diagram, Fig. 22, select the point corresponding to the initial steam condition, and read off total heat, H_1; follow down the vertical line (constant entropy), to the back pressure in the case, and read off total heat, H_2, in the final condition. The available heat-drop is H_1-H_2:

$$\text{Efficiency of Rankine cycle, } E_r = \frac{H_1 - H_2}{H_1}$$

$$\text{Steam-consumption of cycle, } W_r = \frac{2545}{H_1 - H_2}, \text{ per i.h.p.-hr., or brake h.p.-hr.}$$

$$= \frac{3413}{H_1 - H_2}, \text{ per kw.h.}$$

$$\text{Heat drop actually obtained, } H_2 = \frac{2545}{W}, \text{ per i.h.p.-hr., or per brake h.p.-hr.} = \frac{3413}{W}, \text{ per kw.h.}$$

where W is the actual steam consumption for the above units.

Thermal efficiency of the actual engine,

$$E = \frac{H_2}{H_1}$$

$$\text{Efficiency ratio} = \frac{H_2}{H_1 - H_2}, \text{ or } \frac{W_r}{W}, \text{ or } \frac{E}{E_r}$$

Having obtained the available heat drop, select the efficiency ratio for the size and type of engine, and multiply the two to get H_2, then

$$W = \frac{2545}{H_2} \text{ per i.h.p.-hr., or per brake h.p.-hr.} \quad (36)$$

$$= \frac{3413}{H_2} \text{ per kw.h.} \quad (37)$$

203. Water rates vary greatly with steam pressure, superheat or moisture, and back-pressure. No comparison of water rate alone can be fair, unless the steam conditions are known. The efficiency ratio is the best means of comparison for varying steam conditions. For small non-condensing engines, the efficiency ratio varies from 0.50 to 0.65; condensing lowers the ratio about 0.10 to 0.15. The reason is that in condensing single engines, the toe of the diagram is cut off and expansion is very incomplete. The same is true of compound engines. Another reason is that the shorter cut-off employed with condensing engines induce a greater amount of cylinder condensation. Of course, the greater thermal efficiency of the cycle, due to dropping the backpressure, more than offsets this reduction in efficiency of *utilization* of the cycle. The efficiency ratio is a measure of efficiency of *utilization*.

204. The thermal equivalent of a horse-power hour is 2545 B.t.u. Large high-grade engines actually develop a horse-power on 15,600 to 17,000 B.t.u.; small engines, 25,000 to 34,000 B.t.u. The thermal equivalent of a kw.h. is 3415 b.t.u. The b.t.u. per kw.h. will vary from 13,500 in a 30,000-kw. turbine to 38,000 in a small steam-engine driven generator.

205. The effect of raising the back-pressure upon an engine can readily be seen from the Mollier diagram; the available adiabatic heat drop is reduced and consequently, although the efficiency ratio may not change, the thermal efficiency of the Rankine cycle is reduced, and therefore the thermal efficiency of the actual engine. In other words, the water rate increases. Since the heat drop is less, there will be somewhat more heat per lb. in the exhaust.

206. Exhaust steam turbines are of valuable use in connection with non-condensing engines used intermittently. The economy of such engines (say, for rolling mill service) is low, and large quantities of steam are exhausted to the air one moment, and almost none the next.

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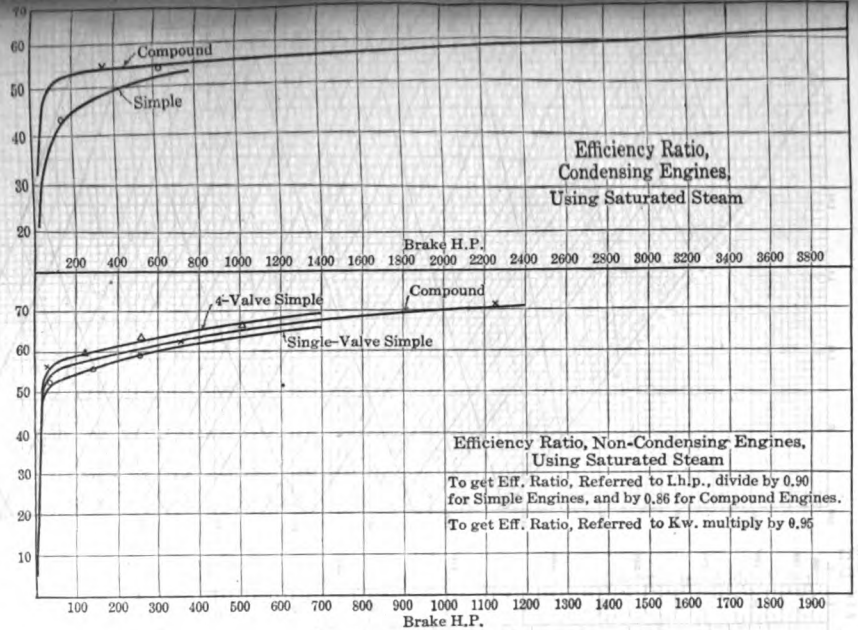


FIG. 21.—Efficiency ratios.

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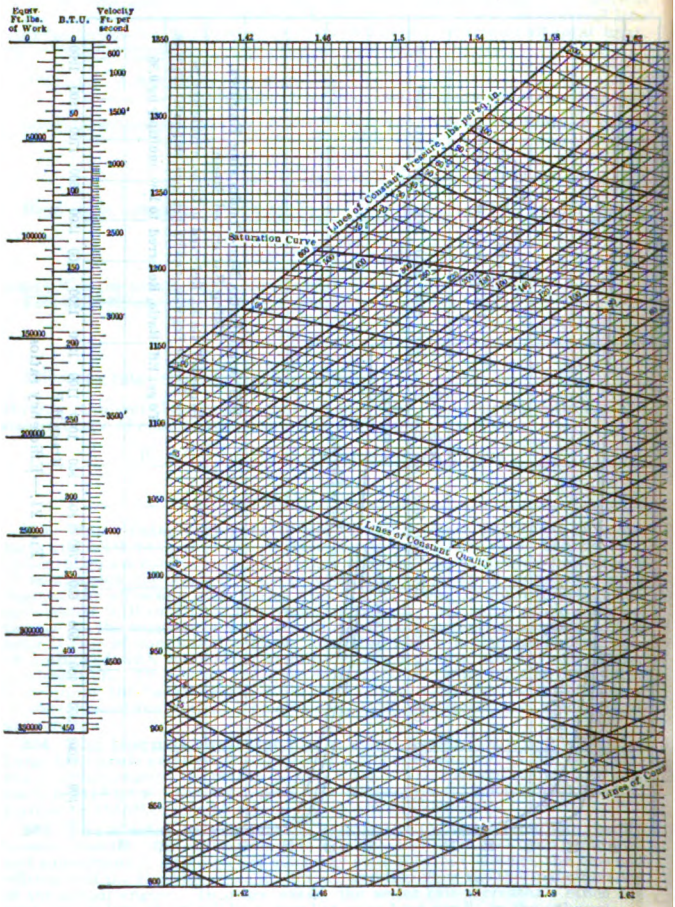
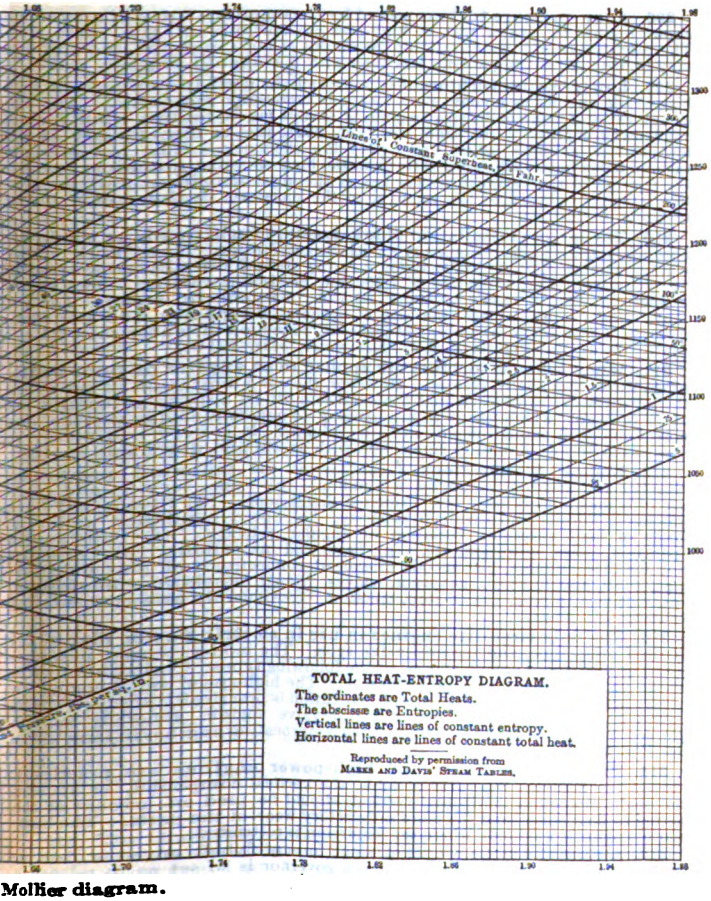


FIG. 22.—

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Mollier diagram.

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207. Regenerators. The exhaust of several such engines (Par. **206**) is piped to regenerators, which are simply heat reservoirs containing a large body of hot water in contact with the exhaust steam. The effect of the regenerator is to absorb heat, when delivered in excess, by condensation of steam; and to release it upon shortage, by evaporation of some of the water. The slight pressure variations between full delivery and shortage are sufficient to accomplish this.

208. A low-pressure turbine served by the regenerator will operate on about double the water rate of high-pressure machine of the same size. The resulting overall water rate for the output of both engines and turbines may be from 20 to 50 per cent. less than with the original engines alone.

209. Low-pressure turbines may sometimes be used in connection with high-grade engines as a convenient means of increasing capacity. The efficiency ratio of non-condensing engines is always much higher than that of condensing engines of the same size (Par. **202**); this is due mainly to the low-pressure cylinder, which has a very low efficiency. The low-pressure turbine has a better efficiency ratio than the high-pressure machine, because the friction of the steam is always less at the lower densities, and the friction is again reduced by the removal of the moisture in the steam before reaching the turbine.

210. The largest installation of low-pressure turbines is at the Interborough Rapid Transit Company's 59th-Street Station, New York. Five Curtis turbines of 7,500 kw. maximum rating are individually connected to five compound Corliss engines of 7,500 kw. maximum rating. The steam pressure is 190 lb. gage; vacuum, 28.5 in.; moisture in steam, 1.5 per cent. The net results are: increase of economical capacity, 146 per cent., increase of maximum capacity, 100 per cent. reduction of water rate, 25 per cent. (Stott and Pigott; A. S. M. E. Trans.; Mar. 1910.)

211. When exhaust turbines are applied to an engine of poor economy, the saving is even greater. However, there is a limitation to the use of the low-pressure turbine, in that the engines must be able to withstand the extra pressures which result from changing to non-condensing service, and must be in good enough condition to be reliable. It is very bad policy to make such an installation in connection with an old and unreliable engine.

212. Engine specifications should cover the following points; (a) Number and location; character of building. (b) Type, service, and manner of connection to load. (c) Principal dimensions. (d) Steam and back pressures, normal and overload capacity. (e) Speed regulation under all kinds of load variation; variation of angular velocity. (f) Satisfactory operation, noise, vibration, etc. (g) Tests and inspection. (h) Construction details—cylinder, piston-rods, crosshead, connecting-rod, pins and bearings, shaft and flywheel, governor, valves, frame, foundation, lubricators, and receivers, piping, engine-stop, erection. (i) General: arrangements for delivery into plant.

213. The only large-size engines in use in electric power plants are of the Corliss type, and the grid-valve type. The moderate-size, medium-speed or high-speed engine may be of the following types: Corliss, automatic piston valve, or Lentz type poppet valve. The high-speed small engine for exciter service or small direct-current generation is practically always a shaft-governor automatic slide-valve or piston-valve engine, generally simple. No new power plants are now built using reciprocating engines in large sizes: See Par. **218.**

214. The medium-power and high-power engines are practically always compound. Wherever possible, the vertical compound, or at least the angle compound (horizontal-vertical) should be used on account of the saving in floor space, and the more satisfactory wear of the parts. The horizontal engine is used only where the headroom is restricted.

215. Automatic stops consist of some form of flyball governor, belt or chain driven from the engine shaft: the governor is so set as to release a trigger or close an electric circuit when the predetermined speed is exceeded. This trigger, or a magnet in the electric circuit, releases a weight arranged to close the throttle. The usual connection consists of a steel wire rope around a drum on the throttle valve stem. In another form of automatic stop the operation of the magnet or trigger releases the pressure of steam on a pilot

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pipe line; this in turn releasing the pressure behind a piston in the specially designed **throttle valve**, which then closes. Both the systems are arranged for additional operation by hand.

216. The operation of steam engines, after correct adjustment of moving parts has been made, is chiefly a matter of lubrication. In **starting**, the usual procedure is to "crack" the throttle in order to admit a little steam to warm up the engine all over without allowing it to turn. After the preliminary **warm-up**, **standing**, the engine is allowed to turn over slowly for a few minutes to **warm** all parts thoroughly; it is then ready for full speed and load. Five minutes may be long enough for **"warming up"** an engine of 300 h.p. or less; 15 or 20 min. are required for large machines. Just before **starting**, a few strokes of the hand oil pump (usually attached) should be given, to insure thorough lubrication. All automatic oiling rigs should be started a few minutes before turning over. Drips should be wide open while warming up, and while turning slowly, but closed when the engine is brought up to speed. **Shutting down** only requires the closing of the throttle, shutting off automatic feeds, and the opening of drips. All bolts and nuts should be gone over periodically, say once a month, and a thorough overhauling given the piston, cylinder, bearings, etc., once a year.

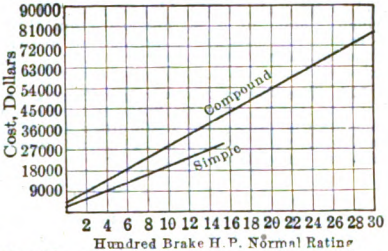


FIG. 23.—Cost of large reciprocating engines.

217. Engine costs. Figs. 23 and 24 give the usual costs of large and small engines. The cost per lb. of engine varies from \$0.10 to \$0.15.

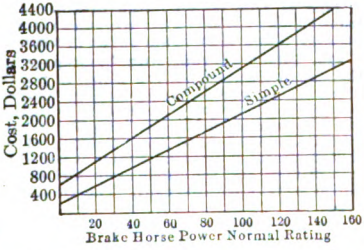


FIG. 24.—Cost of small reciprocating engines.

218. The present status of the reciprocating engine is revealed by a progressively diminishing percentage of the total h.p. of prime movers sold. The large steam turbine has totally displaced it in central stations; and recently the development of fairly economical small turbines is cutting down the field in all directions. The immense advantages of the turbine are great enough to overcome a slight inferiority in water rate in the small sizes. Ultra-conservatism and ignorance of the real cost of power, of which coal and water are only fractional parts, account for the purchase of reciprocating engines where turbines ought to be installed. The oil engine and the gas engine, for small and moderate sized plants, are also giving the steam engine competition, in localities where the cost of oil, or producer gas, will permit.

STEAM TURBINES

219. The thermodynamics of the steam turbine is a simpler matter in theory than the steam engine. The energy of the adiabatic expansion in the turbine is converted into kinetic energy by producing motion of the steam particles, which issue from the nozzles as jets.

220. Resisted and free expansion. The expansion in the engine is termed "perfectly resisted;" in the turbine it is "free." Therefore all the work is done upon the steam itself during the expansion, producing high

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velocity of the steam particles; these particles in turn impinge upon curved vanes or buckets, which change the direction of flow of the jets in such a manner as to produce a force in the direction of rotation of the wheel.

221. The losses are wholly different from those in the engine; there is no initial condensation, because the parts assume the temperatures of the moving steam, instead of being alternately heated and cooled, and radiation is so slight as to be negligible (0.1 per cent. or less).

222. Friction. The only true mechanical friction is in the bearings and governor mechanism and is usually under 2.5 per cent. in small turbines, and under 1 per cent. for larger sizes. The principal loss is steam friction, which is made up of (a) nozzle friction, (b) blade friction, (c) eddies in the flow and (d) windage of the discs or drums revolving in steam. There is some **leakage**, but generally less than in the engine. The velocity of the exhaust steam is also a source of direct loss.

223. The flow of gas or vapor through a nozzle is a phenomenon divisible into two classes—(a) above, and (b) below, the critical pressure. When difference of pressure is maintained across an orifice, steam will flow with increasing velocity and in increasing quantity as the pressure difference increases up to that point at which

$$\frac{P_2}{P_1} = 0.58, \text{ for steam,} \tag{38}$$

where P_1 = initial pressure in lb. per sq. in. absolute and P_2 = back pressure in lb. per sq. in. absolute.

224. The critical pressure is,

$$P_2 = 0.58P_1. \tag{39}$$

This is true for all initial pressures. The corresponding velocity varies from 1,300 to 1,500 ft. per sec., and is found practically to coincide with the velocity of sound in steam at the pressure $P_2 = 0.58P_1$.

225. Effect of reducing back-pressure. Up to this point (Par. 223) the stream issues from the orifice in parallel lines; but if the value of P_2 is reduced below $0.58P_1$, no further increase in velocity or quantity can be obtained, at the orifice, but there is further acceleration beyond the orifice, and the stream flows out laterally as well as forward. Heavy accoustic vibrations occur, and the efficiency of conversion decreases. To correct this, a conical or conoidal section is added to the orifice, diverging in the direction of flow, and the further pressure drop is permitted to take place in this flaring or trumpet-like exit. The De Laval nozzle was the original divergent type.

226. The exit area should be that suited to the velocity and volume resulting from the total heat drop from the pressure P_1 to P_2; but the throat always remains of that size required for a pressure of $0.58P_1$, and a velocity of about 1,300 to 1,500 ft. per sec. The theoretical velocities are not realized, due to friction of the steam in the nozzle.

227. The velocity efficiency of a convergent nozzle (orifices with rounded entrance) varies from 98 per cent. at low velocities down to 95 per cent. at 1,300 to 1,400 ft. per sec. The **velocity efficiency of a divergent nozzle**, for expansion beyond the critical pressure, ranges from 94 per cent. at 1,500 ft. per sec. to 90 per cent. or 85 per cent. at 3,000 ft. per sec.

228. The velocity efficiency of the buckets varies from about 95 per cent. to 98 per cent., for the low velocities used in reaction turbines (less than 1,000 ft. per sec.), to 84 per cent. or 86 per cent. in impulse turbines at velocities of about 2,500 ft. per sec. The second and succeeding rows of buckets or guides in velocity-compounded turbines have even lower efficiencies, reaching 84 per cent. at about 1,500 ft. per sec.

229. The velocity obtainable by expansion is expressible by

$$V = 223.7\sqrt{H_1 - H_2} \tag{40}$$

where V = velocity at exit of nozzle in ft. per sec., H_1 = total heat contents of steam at initial condition, and H_2 = total heat contents of steam at final condition. If H_2 denotes the heat contents after an adiabatic expansion, it follows that V is the theoretical value; but H_2 is always higher than this, because internal friction reduces the quantity of heat removed from the steam by the work done.

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230. Pressure drop. In the impulse turbine, all pressure drop occurs in stationary nozzles, and there is no difference of pressure across the moving blades. In the reaction type, about half the pressure drop takes place in the stationary blades, and the remainder in the running blades; and the latter, therefore, act also as nozzles. There is an unbalanced force due to this difference of pressure across the moving blades that must be cared for by balancing devices.

231. There are two basic types of turbines: impulse and reaction. Either of the two is really pure impulse or pure reaction, but the work done by impulse predominates in the impulse type, and the work by reaction in the reaction type. The simple impulse wheel is only employed in the single-stage de Laval type; velocity compounding and pressure compounding are employed in all other impulse types. Compounding becomes a necessity, to secure reasonable rotative speeds.

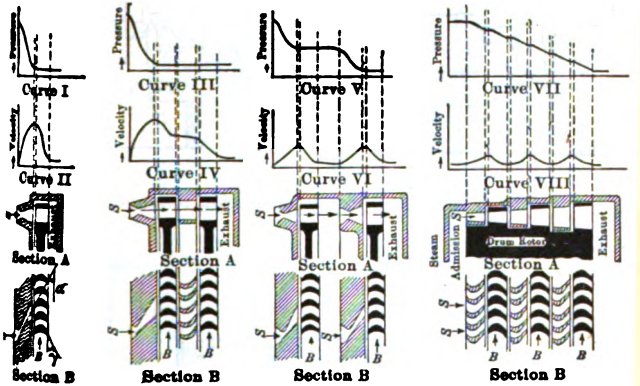


FIG. 25.—Elemental turbine types.*

232. The steam velocity in a single expansion from 150 lb. gage to a 28-in. vacuum would be about 3,100 ft. per sec. For best efficiency the blade velocity should be a little less than half the steam velocity, or in this case 1,500 ft. per sec., which results in centrifugal stresses in the disc much in excess of suitable stresses for commercial materials. If the wheel is run slower, the exit velocity of the issuing steam is increased, reducing the efficiency.

233. In velocity compounding the exit velocity from the first wheel is received in a series of guide blades and redirected to a second wheel, so that more of the energy is removed, without unreasonable wheel velocities (300 to 725 ft. per sec.).

234. Pressure compounding is the division of the pressure drop into two or more stages, which are essentially de Laval single-stage nozzles and wheels in series. Fig. 25 shows these types with characteristic figures.

235. The reaction turbine for best efficiency runs at $\sqrt{2}$ or 1.414 times the peripheral speed of the impulse turbine for the same pressure drop. It is never built single-stage, but always pressure-stage compound.

236. Principal types. The de Laval is the original single-stage impulse type; the velocity-compounded type (generally also combined with few-stage pressure compounding as well) is usually known as the Curtis; the pressure-stage type (pure), as the Rateau; and the reaction type, as the Parsons.

* From "The Steam Turbine" by J. A. Moyer.

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237. The blading of the three principal types, Parsons, Curtis and Rateau, is shown in Figs. 26, 27, and 28.

238. Hybrid types have lately proved the most efficient, or cheaper to build. In moderate sizes the Parsons turbine is built with a Curtis 2-wheel velocity stage for the high-pressure stage; the advantage is a large pressure drop in a small nozzle chamber, avoiding high pressure in the casing, shorten-

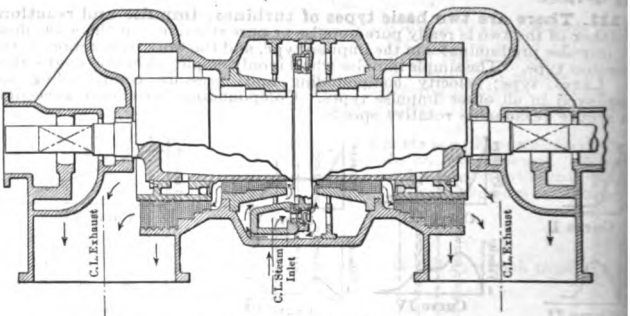


FIG. 26.—Curtis-Parsons double-flow turbines.

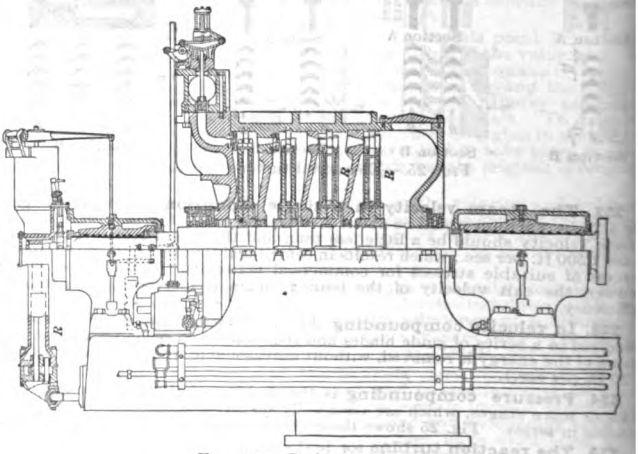


FIG. 27.—Curtis turbine.

ing and cheapening the construction, and eliminating the short high-pressure reaction blading, which is the least efficient.

239. The Curtis-Rateau type consists of a 2-wheel Curtis element for the high-pressure stage, followed by 6 to 12 Rateau pressure stages. It has the same advantage with regard to keeping the high-pressure out of the casing.

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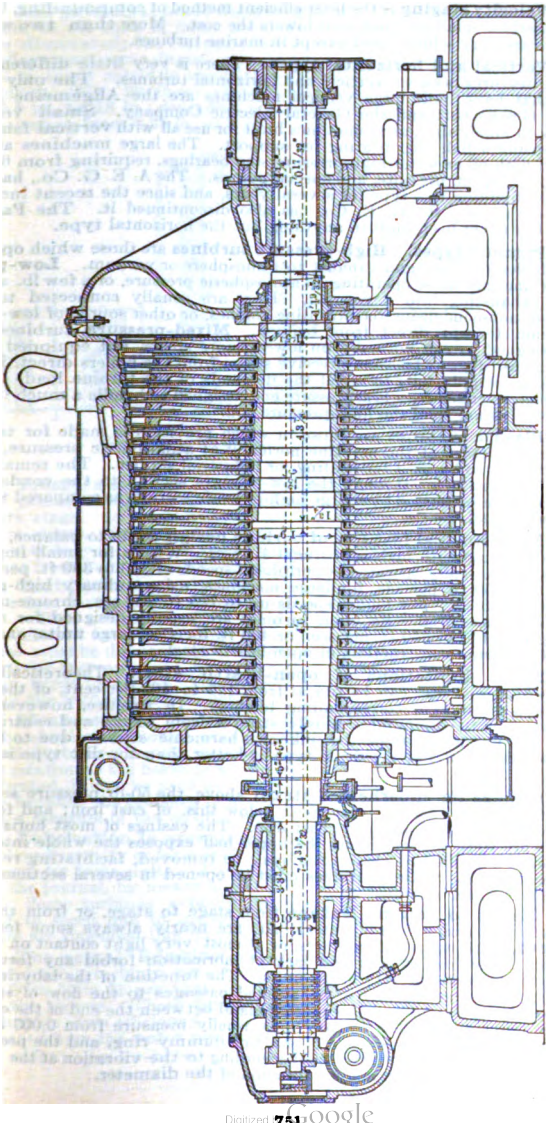


FIG. 28.—Rateau turbine.

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240. Velocity staging is the least efficient method of compounding, but is chiefly used for small turbines, as it lowers the cost. More than two wheels per stage are very seldom used except in marine turbines.

241. Vertical and horizontal types. There is very little difference in principal features between vertical and horizontal turbines. The only companies that have built large vertical machines are the Allgemeine Elektricitäts Gesellschaft and the General Electric Company. Small vertical turbines, in small sizes, are sometimes built for use all with vertical fans and pumps, using a ball step bearing for support. The large machines are all provided with oil or water high-pressure step bearings, requiring from 650 to 1,000 lb. per sq. in. pressure, and special pumps. The A. E. G. Co., has discontinued building this type for several years, and since the recent increase in rotative speeds, the G. E. Co. has also discontinued it. The Parsons turbine has never been built in anything but the horizontal type.

242. Pressure types. High-pressure turbines are those which operate on full boiler pressure and exhaust to atmosphere or vacuum. **Low-pressure** turbines are those operating on atmospheric pressure, or a few lb. above it, and exhausting into a vacuum. They are usually connected to the exhaust of non-condensing reciprocating engines, or other source of low-pressure steam (except direct from boilers). **Mixed-pressure** turbines are those designed to run normally on low-pressure steam, but equipped with high-pressure stages which may receive steam from the boilers direct, if the low-pressure supply fails to equal the demands of the turbine load. This type is characterised by a low-pressure end designed to handle a much larger quantity of steam than the high-pressure end.

243. Bleeder turbines are those in which provision is made for taking steam from a stage of the machine normally at atmospheric pressure, or a few lb. above, to be used for heating, or industrial service. The remainder not so used continues through the low-pressure section to the condenser. This type is characterised by a large high-pressure section, as compared to the low-pressure end.

244. The principal features of turbine design relate to balance, leakage, and resistance to high centrifugal stresses. Wheels for small impulse turbines are normally operated at peripheral speeds of 250 to 350 ft. per sec., and 400 to 550 ft. per sec. for large machines, using ordinary high-grade open-hearth steels. For higher speeds up to 725 ft. per sec. chrome-nickel forged steels are used. Reaction turbines are usually designed for much lower speeds, 150 to 350 ft. per sec., or 400 ft. for very large units, and are generally of drum construction, of open-hearth steel.

245. Speed limitations of open-hearth steel. Theoretically, a properly designed disc can be run at from 125 to 160 per cent. of the safe speed of a drum with corresponding blading. In practice, however, the difference due to computable tensile stresses from blades and centrifugal force is less important than the unknown harmonic stresses due to blade and disc vibration, and the drum type is better than the disc type in this respect.

246. Casings for superheated steam above the 50-lb. pressure section of the turbine are made of cast steel; below this, of cast iron; and for all pressures in saturated steam, of cast iron. The casings of most horizontal turbines are split, so that lifting the upper half exposes the whole interior. With one more lift, the whole rotor may be removed, facilitating repairs to all parts. The vertical turbines must be opened in several sections and taken apart wheel by wheel.

247. Glands to prevent leakage from stage to stage, or from the interior of the turbine to the outside air, are nearly always some form of **labyrinth,** with no actual contacts, or at most very light contact on floating rings. The high speeds and lack of lubrication forbid any forms of soft packing except for very small units. The function of the labyrinth is to interpose a large number of constricted passages to the flow of steam. The Parsons turbine uses a water-sealed gland between the end of the casing and the outer air. These constrictions usually measure from 0.003 in. to 0.035 in., depending on the size of shaft or dummy ring, and the pressure difference. The clearance is selected according to the vibration at the point of application and is often made a function of the diameter.

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248. The principal blade fastenings consist of the dovetail for impulse elements, in all sorts of forms from square T-heads to bulb heads with all corners eliminated; the reaction blading of Parsons make is a caulked type, depending upon some distortion and friction for the grip. Riveted blading is used to some extent in small impulse turbines, but has been a failure in large discs. Fig. 29 shows three sucessful types. **Blade heights** vary from 0.5 in. to 18 in., depending on the size of the machine, and the stage. Widths range from 0.25 in. to 2 in.

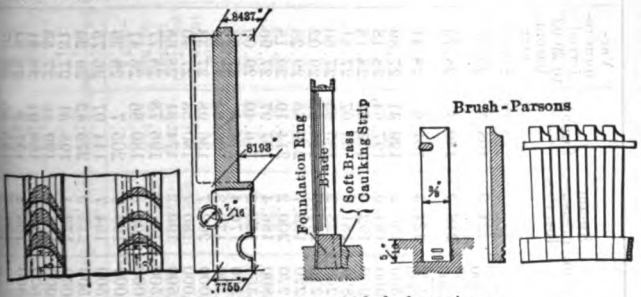


FIG. 29.—Four types of blade fastenings.

249. Pressure stages. In high-pressure Curtis turbines, the usual number of pressure stages is five to seven, with two velocity stages in each pressure stage. In Rateau types, there are about thirteen to twenty-two pressure stages, with one wheel in each; or one Curtis stage of two velocity stages may take the place of two or three high-pressure stages. The Parsons type has from forty to seventy pressure stages.

250. Turbine rating. Impulse turbines are rated on a basis of calculated flow through the nozzles and known efficiencies of different types of wheels. Thus a wheel of given size may be of widely varying horse-power under different areas of nozzles; the efficiencies also are altered. Reaction turbines must be designed for the load, and can only be altered in best load capacity by increasing the initial pressure. Overload is provided for in the impulse types by adding extra nozzles; in the reaction type by by-passing some of the high-pressure stages.

251. Measurement of shaft output. The output of the turbine must be obtained by brake, or electrically; no indicated horse-power exists; in small turbines, throttle governed, the steam-chest pressure bears an accurate relation to the horse-power delivered at any speed, and if the turbine is calibrated, it may be used as an indication of the output thereafter. This is true because the pressure is a measure of the steam flow, and the steam flow is a measure of the output, for any given turbine efficiency.

252. Lubrication is exceedingly simple. No internal oiling whatever is employed; gravity or force feed with copious supply at 15 to 25 lb. pressure is general for large units. The speed of rotation causes a dragging of oil under the journal, by means of viscosity, so that the journal never rides on metal. Some turbines actually rise a few thousandths of an inch after coming to speed due to increase in the oil film under the journal. Small turbines are ring-oiled like motors.

253. The actual Rankine-cycle efficiency ratios obtained in small non-condensing turbines vary from 45 per cent. to 50 per cent.; for large units, from 55 to 65 per cent. for the great majority, up to 80 per cent. as about the highest. These figures assume condensing service in each case. This table gives efficiency ratios and B.t.u. per kw-hr. The latter figure is obtained from the water rate and the steam conditions.

$$\text{B.t.u. per kw-hr.} = \frac{W \times (H_1 - q_3)}{} \qquad (41)$$

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254. Turbine Performance: Data on Commercial Tests of Large Steam Turbines
(Christie[5])

	Maker of turbine	Type	Date of test	Load, kw.	R.p.m.	Steam pressure, lbs. abs.	Supht.	Vacuum referred to 29.92" barometer	Pounds of steam per kw.-hr.	Efficiency ratio
1	Westinghouse	Parsons	1913	26,740	750 1,500	224.0	108.5	28.86	11.26	75.84
2	Westinghouse	Parsons	1913	32,348	750 1,500	218.2	130.4	28.75	11.33	75.34
3	Westinghouse	Parsons	1913	16,342	750 1,500	224.3	101.6	28.41	11.77	72.54
4	Erste Brunner M. F. G.	Curtis-Parsons	1910	2,128	1,500	156.2	120.31	27.89	13.82	71.8
5	Erste Brunner M. F. G.	Curtis-Parsons	.....	6,060	960	184.9	197.64	28.18	12.56	71.3
6	Erste Brunner M. F. G.	Curtis-Parsons	1910	7,442	960	192.0	205.51	28.18	12.625	70.3
7	Westinghouse Machine Co.	Curtis-Parsons	1910	9,173	1,800	181.7	59.07	27.81	14.57	68.9
8	Erste Brunner M. F. G.	Curtis-Parsons	1910	1,416	1,260	128.2	135.69	27.60	15.18	68.8
9	Brown-Boveri & Cie	Parsons	1910	6,257	1,210	203.7	175.57	29.02	11.95	68.8
10	A. E. G.	Curtis-Rateau	1911	6,518	1,220	198.7	219.66	29.28	11.43	68.7
11	A. E. G.	Curtis-Rateau	1911	6,565	1,220	200.2	214.19	29.18	11.64	68.5
12	Allis-Chalmers	Parsons	1908	4,300	1,800	186.4	107.97	27.96	14.02	68.4
13	Brown-Boveri & Cie.	Curtis-Parsons	.....	3,053	1,360	150.2	146.40	29.00	13.01	68.0
14	Brown-Boveri & Cie.	Curtis-Parsons	1911	1,750	1,500	176.4	214.5	27.08	14.23	67.5
15	M. A. N.	Curtis-Zoelly	.....	3,584	1,500	178.3	196.63	27.54	13.99	67.5
16	James Howden & Son	Zoelly	1909	6,383	1,000	202.7	136.98	27.33	14.305	67.5
17	M. A. N.	Zoelly	1910	1,400	3,000	180.7	180.53	27.40	14.21	67.4
18	British Westinghouse	Curtis-Rateau	1911	5,066	1,500	190.2	174.31	28.68	13.00	67.0
19	Brown-Boveri & Cie.	Curtis-Parsons	1910	3,764	1,500	161.2	196.78	28.77	13.04	66.8
20	Brown-Boveri & Cie.	Curtis-Parsons	1911	1,495	3,000	200.6	180.86	26.41	14.78	66.8
21	Escher Wyss & Co.	Zoelly	1910	2,052	3,000	193.9	205.7	28.39	13.04	66.6
22	British-Thomson-Houston	Curtis	1911	2,927	1,500	154.7	144.07	26.75	15.96	66.5
23	Oerlikon	Rateau	1911	3,166	1,500	213.9	275.42	29.25	11.44	66.1
24	Brown-Boveri & Cie.	Curtis-Parsons	1911	1,271	3,000	172.1	198.51	27.31	14.61	65.9
25	Escher Wyss & Co.	Zoelly	.....	5,118	1,000	133.7	199.48	27.55	15.18	65.7
26	Bergmann	Curtis-Rateau	1910	2,477	1,500	140.0	168.91	28.81	13.93	65.6
27	Brown-Boveri & Cie.	Parsons	1903	3,500	1,360	156.4	137.2	28.84	13.71	65.6
28	Westinghouse Machine Co.	Curtis-Parsons	.....	11,466	750	191.7	105.65	28.07	14.45	65.5
29	Escher Wyss & Co.	Zoelly	1910	4,189	1,000	179.7	183.98	28.66	13.30	65.5

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254. Turbine Performance: Data on Commercial Tests of Large Steam Turbines.—(*Continued*)

	Make of turbine	Type	Date of test	Load, kw.	R.p.m.	Steam pressure, lbs. abs.	Supht.	Vacuum referred to 29.92″ barometer	Pounds of steam per kw.-hr.	Efficiency ratio
30	Escher Wyss & Co	Zoelly	.....	3,540	1,500	155.1	107.86	28.21	15.07	64.8
31	F. Ringhoffer	Zoelly	1908	3,000	1,000	170.7	101.18	27.60	15.52	64.8
32	M. A. N	Zoelly	1910	1,250	3,000	182.1	207.89	28.82	13.09	64.4
33	Brown-Boveri & Cie	Parsons	.....	3,000	1,360	165.0	258.91	27.02	14.75	64.3
34	C. A. Parsons & Co	Parsons	.....	5,164	1,200	214.3	131.26	28.95	13.18	64.3
35	Escher Wyss & Co	Zoelly	1910	1,641	3,000	221.0	281.63	27.91	13.08	64.1
36	Erste Brunner M. F. G	Curtis-Parsons	.....	1,250	3,000	184.9	197.64	27.89	14.32	63.9
37	Escher Wyss & Co	Zoelly	1908	5,000	1,000	164.4	173.21	26.38	16.13	63.9
38	British-Thomson-Houston	Curtis	1909	2,500	1,500	126.5	68.70	28.47	15.92	63.7
39	General Electric Co	Curtis	.....	3,464	.....	210.0	126.98	28.75	13.62	63.6
40	A. E. G	Curtis	1909	2,236	1,500	191.6	275.69	29.34	11.77	63.6
41	Allis-Chalmers	Parsons	1911	3,850	1,800	164.7	125.06	27.91	15.40	63.5
42	A. E. G	Curtis	1906	3,000	1,500	191.3	211.82	29.05	12.79	63.4
43	General Electric Co	Curtis	.....	8,880	.....	192.5	106.30	28.02	15.05	63.1
44	A. E. G	Curtis-Rateau	1907	3,169	1,500	184.7	216.78	29.11	12.74	63.0
45	Brown-Boveri & Co	Curtis-Parsons	1910	3,320	1,500	180.9	151.44	29.02	13.50	63.0
46	General Electric Co	Curtis	.....	10,816	750	190.0	174.39	29.39	12.90	61.9
47	General Electric Co	Curtis	.....	5,095	.....	185.1	198.55	29.40	12.71	61.6
48	British-Thomson-Houston	Curtis	1911	8,775	750	194.0	71.65	27.95	15.95	61.0

*A. G. Christie, *Trans.* A. S. M. E., 1912, and R. J. S. Pigott.

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Where H_1 = heat contents of steam supplied to turbine, q = heat of the liquid in condensate and W = water rate in lb. per kw-hr.

The thermal efficiency is the product of the efficiency ratio and the thermal efficiency of the Rankine cycle (adiabatic expansion).

255. Efficiency ratios. Figs. 30, 31, and 32 give characteristic efficiency ratios for small and large units. It is found that the **Willans line** (total

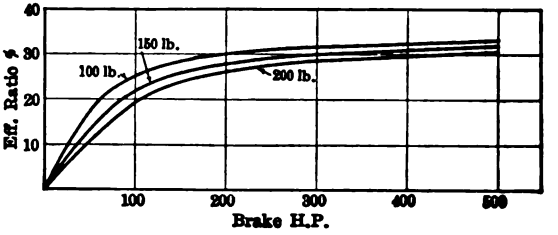


FIG. 30.

steam per hour vs. output) is practically straight line from zero load to full (or best) load; on overload, with by-pass, or extra nozzles open, it is usually another straight line, joining the first at best load, but more steeply inclined. This property allows fractional-load water rates to be readily interpolated from one or two load tests or guarantees.

The full load water rates can be obtained from the efficiency ratio values, in the way given in Par. **202**. The no-load steam consumption will be approximately 6 to 7 per cent. in 30,000 kw. sizes, 8 to 10 per cent. for 2,000 to 5,000 kw. and 12 to 15 per cent for sizes under 500 h.p

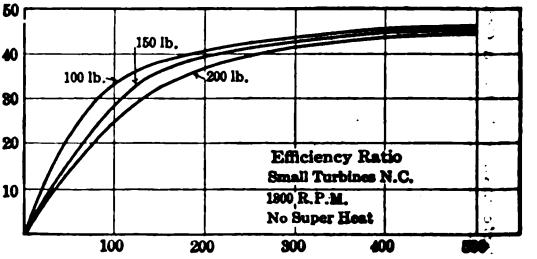


FIG. 31.

256. The effect of variation in vacuum on a turbine differs somewhat with the type of machine, but can be obtained with reasonable accuracy from Fig. 33, which gives average figures for high-pressure turbines; Fig. 34 applies to low-pressure turbines. A vacuum of 28 in. is taken as the standard for high-pressure, and 27.5 in. for low-pressure units.

257. The effect of superheat in improving economy is usually taken at the rate of 10 per cent. for the first 100 deg. of superheat, 8 per cent. for the next 100 deg., and 7 per cent. for the third hundred. Figs. 33 and 34 show the corrections, which are practically identical for all types.

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258. The efficiency losses may be subdivided into (a) nozzle friction, 6 to 28 per cent.; (b) blade friction, 6 to 30 per cent. (c) windage, 3 to 15 per cent.; (d) unused exit velocity, 3 to 5 per cent.; (e) leakage 2 to 10

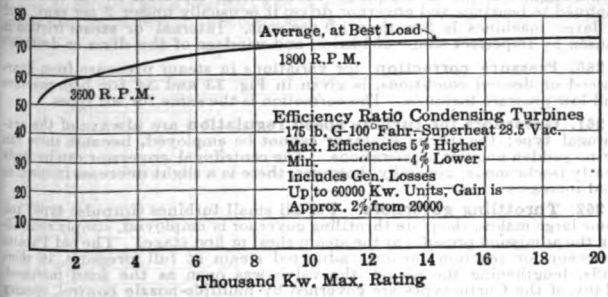


FIG. 32.

per cent.; (f) mechanical losses, 1 per cent. As all the steam losses in the high-pressure stages reappear in the steam as unused heat, the available heat drop is increased by translation of the expansion lines to higher entropies, as shown by the **Mollier diagram,*** given in Fig. 22, and hence the whole

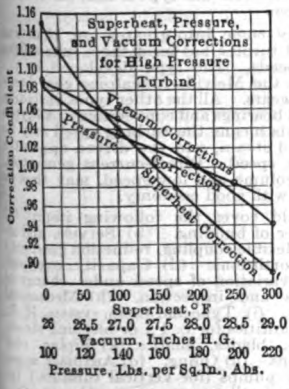


FIG. 33.—Superheater pressure and vacuum corrections for high-pressure turbines.

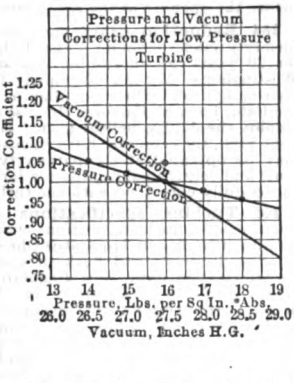


FIG. 34.—Pressure and vacuum corrections for low-pressure turbines.

turbine-diagram efficiency in a multi-stage turbine is always from 2 to 6 per cent. higher than that of the individual stages.

259. The efficiency of the turbine, though different for different speeds and pressures, does not change appreciably with time or service.

* Marks & Davis "Steam Tables," Longmans, Green & Co., N. Y., 1912.

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The shaft horse-power or brake horse-power is from 3 to 15 per cent. less than the calculated diagram horse-power (corresponding to i.h.p. in the engine). The usual friction losses are generally less than one-half those of steam engines of the same rating. **Mechanical friction** in the turbine is confined to bearings and governor drive; it is usually under 2 per cent., and in large machines is less than 1.0 per cent. Internal or steam friction is caused by imperfect shape of blades, and windage of the discs or drums.

260. Pressure correction, for variations in steam pressure from guaranteed or desired conditions, is given in Fig. 33 and 34 for high-pressure and low-pressure turbines. The correction is the same for all types.

261. Governors for turbine speed regulation are always of the centrifugal type; the inertia governor cannot be employed, because there can be no sudden angular accelerations. The centrifugal governor can be made nearly isochronous; generally, however, there is a slight decrease in speed as load increases.

262. Throttling governors. For all small turbines (impulse type) and some large makes, the plain throttling governor is employed, simply controlling the admission pressure at the steam chest or first stage. The old Parsons governor for reaction turbines admitted steam at full pressure, in short puffs, lengthening the period the valve was open as the load increased. Many of the Curtis types are governed by multiple-nozzle control, opening and closing individual nozzles, from 6 to 16 in number, and thus controlling the quantity of steam to the first stage only.

263. Parsons governor. In the Parsons machine, the governor not only controls the primary throttle, but also a secondary valve admitting live steam in one-sixth to one-fourth the total number of stages, further down the turbine. This virtually cuts out of service the by-passed rows, and converts the turbine into one of fewer stages, but in effect having larger blade dimensions, and not as economical. The best load for this type is that carried just before the opening of the secondary valve.

264. Reduction gears have recently come into greater use, than was formerly made of them. The de Laval turbine has used them successfully for 20 years, at enormous relative speeds. The type developed by the Westinghouse Machine Company from the Melville-Macalpine gear has a floating hydraulic frame for aligning the gears. All the other types, including the Falk, Fawcus, Parsons, etc., use solid bearings and connections. All types employ the double helical gear. By this means the turbine speed may be kept high, for economy both in cost and steam, and the driven apparatus may be operated at comparatively low speed. Direct-current generators, fans, and centrifugal pumps for large volume and low speed, may thus be successfully combined with the turbine with good economy.

265. Turbine specifications should cover the following items: (a) Number of units and location; character of building. (b) Service, and attachment to driven apparatus (direct, flexible coupling, reduction gear, etc.) (c) Speed, steam and back pressure conditions. (d) Capacity, overload; electric system data. (e) Regulation, variation of speed under change of load. (f) Noise, vibration. (g) Tests and inspection. (h) Mechanical details of connection to driven apparatus. (i) Type and steam system, H. P., L. P., bleeder mixed pressure, giving quantities for L. P., or bleeding steam. (j) Materials—casing, wheels, nozzles, blades, shaft. (k) Piping connections. (l) Bearings. (m) Foundations. (n) Oiling. (o) Auxiliary apparatus—oil pumps, relays, step-bearing pumps (for vertical turbines.) (p) Painting and lagging. (q) Gages and miscellaneous equipment.

266. Turbine supports should always be carefully designed to prevent distortion of the parts; stiffness of the supports is usually very desirable, but great mass is unnecessary; many reaction turbines of large size are running on foundations entirely of steelwork, which is low in mass for the strength and stiffness.

267. The auxiliaries required for horizontal turbines consist only of an **oil pump** for large self-contained units: no auxiliaries are needed for small units.

268. The auxiliaries for vertical units include in addition to the oil pump, **step-bearing pumps** for oil or water, capable of handling pressure

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of 500 to 1,000 lb. per sq. in. (varying with the size of the main unit). These step-bearing pumps, with the piping, are generally in duplicate. In order to steady the oil supply, a frictional resistance called a **baffler** is employed between pump and step bearing; and to remove pulsations of pressure and provide a small reservoir, **accumulators** of the elevator type are also required.

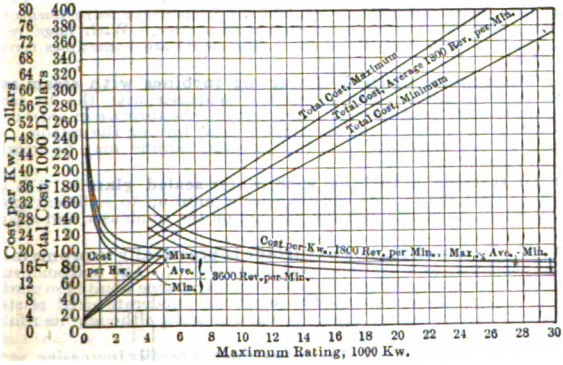


Fig. 35.—Steam turbines. Cost per kw. *vs* capacity. Total cost *vs.* capacity (1920).

60 Cycles, maximum 24 hr. rating, 50 deg. Cent. rise; power factor, 80 per cent.; pressure 175 lb.; superheat, 100 deg. Fahr.; vacuum, 28.5 in.

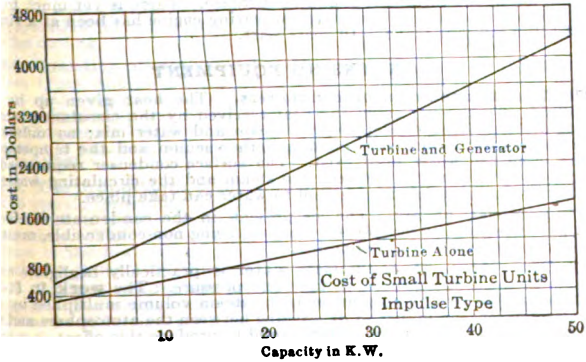


Fig. 36.—Cost of small turbines and generators.

269. The cost of turbines per kw., including generators, varies from $55 for small sizes down to $17 or less for very large units, at normal rating; or at maximum rating, $14. Fig. 35 gives the cost per kw. (normal rating) of large units including generators; Fig. 36 gives the cost per kw. of small turbines with and without generators (1920).

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270. The operation of the steam turbine is remarkable for its simplicity; one oiler can attend to two or three units (on the engine-room floor) aggregating as much as 50,000 or 80,000 kw. But with engines, only 3,000 or 4,000 kw. can be cared for by one man; and in many cases much less. The turbine has a maintenance cost but one-fifth as great as that of the reciprocating engine approximately. There are very few articulated parts in the turbine; its continuous operation is therefore much more reliable and periods of two to four weeks continuous operation are common. **Inspections** made once a year frequently show no repairs or adjustments to be necessary, and the turbine is continued in service. With large reciprocating engines, both inspections and adjustments are sometimes necessary every 24 hr.

271. The general method of starting turbines with steam-sealed glands is to establish a vacuum on the condenser with the dry-vacuum pump, start the circulating water, and "crack" the throttle in order to send steam through the turbine for warming, without turning the spindle. After the proper time allowance (5 to 15 min.) the turbine may be brought to speed and placed under load.

272. In starting a turbine with water-sealed glands, it is usual practice to start the turbine non-condensing until up to sufficient speed to seal the glands, then establish the vacuum on the condenser and apply the load.

273. At the present time the turbine is practically supreme in large central stations, as a heat-operated prime mover. The hydraulic station is limited to certain localities, while the large gas-engine plant is so unreliable as to be out of the question. For small and moderate-sized plants the internal-combustion engine is on a competing basis, although its reliability has never equalled that of the turbine.

274. The field for small steam turbines is readily increasing, particularly since centrifugal boiler-feed pumps, circulating-water pumps, fans, blowers, etc., are successfully designed for turbine speeds, with good efficiencies. The small amount of attention required by the turbine, its reliability and low maintenance are generally more than sufficient to overbalance a slight inferiority to the steam engine in economy. **Since the item of fuel economy is only one of the factors in operating cost,** this result is natural and the use of the turbine is bound to increase. There is yet much to improve in the turbine, whereas the reciprocating engine has been at a virtual standstill in development for 10 years past.

CONDENSING EQUIPMENT

275. Thermodynamics of condensers. The heat given up by the condensing steam must equal the heat received by the circulating water. In jet or barometric condensers, the steam and water mix; no difference between the temperature corresponding to the vacuum and the temperature of the discharge water need exist. The surface condenser requires some difference of temperature between the steam and the circulating water at all times, or no heat flow from steam to water can take place.

276. Removal of air. The air present in the condensate is chiefly drawn in by leakage at the joints. This air, being non-condensible, must be removed by segregation and pumping.

277. The volume of condensate water is practically negligible compared with the steam volume at the same pressure. The **work in ft-lb made available by the condenser** is the steam volume multiplied by the pressure difference in lb. per sq. ft. existing between the atmosphere and the interior of the condenser; the work required to produce this effect, is merely the product of the number of cu. ft. of condensate and the same pressure difference. At 28 in. vacuum the ratio of these two is 21,000 to 1. To the **condensate pump work** must be added the **work of the circulating-water pump** (chiefly a friction loss) and the **work of the dry-vacuum pump** which removes the air.

278. The principal condenser types are: (a) jet; (b) barometric; (c) eductor or siphon; (d) rotary jet; and (e) surface. These are described in Par. **279** to **283.**

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279. The jet condenser consists of a cast-iron shell into which the exhaust pipe is led, having the circulating water sprayed through the chamber in jets. The steam condenses and mingles with the jets, and is pumped out of the bottom of the shell. **The barometric condenser** is a jet condenser set higher than 34 ft. above the level of the discharge well or tunnel; the water therefore runs away by gravity, but must be pumped in, due to a slight friction loss and velocity head, the vacuum assisting the circulating pump.

280. In the eductor or siphon type, the injection water is pumped in under 25 to 30 lb. pressure, and requires sufficient velocity to carry out not only its own mass but the condensed steam and entrained air as well, by kinetic energy. No vacuum pumps are required.

281. The rotary jet types—originally developed by Le Blanc—consist of a centrifugal impeller throwing segments of water into a nozzle, in such fashion as to form water pistons, which trap and condense the steam, and push before them the air. This type is also used as a dry-vacuum pump. All the above types (Par. **279** to **281**) are derivatives of the true jet condenser.

282. The surface condenser consists of a cast-iron shell with two heads or water boxes into one of which the circulating water passes. These two boxes are connected by a large number of small brass tubes, which allow the circulating water to traverse the main shell without contact with the steam; the latter is led into the shell around the tubes. The circulating water passes to the second box, which may lead to the discharge or redirect the water back to another section of the first box by way of another nest of tubes. If the first type is used it is called **single pass**; if the second, **two pass**; and so on, with three or four passes in some few cases. The cold water passing through the tubes condenses the steam by conduction, and the condensate trickles down to the bottom of the shell, there to be pumped out. The air, which is always heavier than steam at the same temperature, also collects at the bottom and must be pumped out, preferably by another pump.

283. Atmospheric condensers consist of a form of surface condenser in which the cooling medium is a mixture of air blast and water spray. The air takes up some of the spray, becoming cooled thereby, and acts as a cooling medium for the steam. High vacuum is not to be obtained with this type. The chief feature is economy of circulating water, which may be in the ratio of 1 lb. of water per lb. of steam, or slightly less, since the whole latent heat of evaporation (of the water spray) as well as the heat of the liquid is available for cooling.

284. Quantity of circulating water required. In the jet or ordinary surface types, the circulating water must be at least 25 to 30 times the weight of the steam condensed. In the jet condenser, the condensate mixes with the circulating water, and, if the latter is dirty, is necessarily lost. The surface condenser keeps the condensate separate from the circulating water, so that it is available for re-use in the boilers, a pure distilled water (Par. **197** and **198**).

285. The proportions of jet condensers are relatively unimportant, the design merely providing for adequate mixture of water and steam. The shell therefore need only be large enough to take the exhaust and water connections. The volume of a jet condenser varies from 0.5 to 2.5 times the volume of the low-pressure cylinder volume of a reciprocating engine; in the eductor types, the volume is somewhat less.

286. Surface condensers are limited in capacity by the rate of heat transfer. For average practice, 300 to 350 B.t.u. per sq. ft. per degree mean temperature difference per hour can be allowed. It follows from this assumption that

$$A = W \times \frac{(H_2 - q_2)}{U \times t_m} \qquad (42)$$

where A = area in sq. ft. of tube surface, W = lb. of steam per hour from exhaust, H_2 = total heat per lb. of exhaust, q_2 = heat of the liquid per lb. (at condensate temperature), $H_2 - q_2$ = 1,000 to 1,050 for most cases, U = transmission coefficient = 300 to 350 B.t.u. per hour, per sq. ft., per degree mean temp. difference (Fig. 37), and t_m = mean temperature differ-

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ence between steam and circulating water. The arithmetic formula for t_m is:

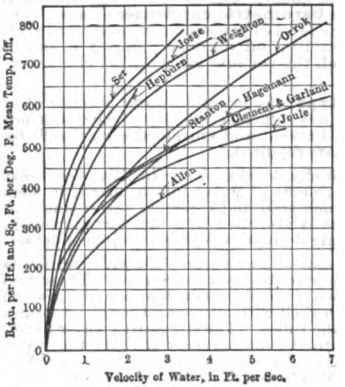


FIG. 37.—Values of the coefficient of heat transmission.

$$t_m = T_s - \frac{(T_1+T_2)}{2} \qquad (43)$$

where T_s = steam temperature at the vacuum, T_1 = injection temperature and T_2 = discharge temperature. The logarithmic formula for t_m is:

$$t_m = \frac{T_2 - T_1}{\log_e\left(\frac{T_s - T_1}{T_s - T_2}\right)} \qquad (44)$$

For the majority of cases, Eq. 43 is sufficient.

287. The quantity of circulating water required for jet condenser is given by

$$W_c = \frac{H_2 - T_2 + 32}{T_2 - T_1} \qquad (45)$$

where Wc = lb. of circulating water per lb. of steam, H_2 = heat contents per lb. of steam, T_2 = discharge temperature, and T_1 = injection temperature. The quantity required in gal. per min., taking $H - T_2 + 32$ as 1050 B.t.u., is

$$S_c = \frac{2.1 W_s}{T_2 - T_1} \qquad (46)$$

where W_s = lb. of steam per hour, and S_c = circulating water in gal. per min.

288. Examples of Modern Condenser Proportions

Name of station	Size of turbo-generators on max. 24-hr. rating	Sq. ft., total	Sq. ft., per kw.
Commonwealth Edison Co.			
Northwest Station	20,000 kw.	32,000	1.60
Quarry St.	14,000	25,000	1.79
Fisk St.	12,000	25,000	2.08
Interborough R. T. Co.			
59th St. Power Station, N. Y., (Engine and low-pressure turbine.)	15,000	25,000	1.67
74th St. Station	30,000	50,000	1.67
Metropolitan St. Ry., Kansas Cy.	10,000	22,000	2.20
Marion Station, P.S.E. Co., N. J.	18,000	25,000	1.39
United El. Lt. & Power Co., N. Y.	15,000	25,000	1.67

289. The quantity of circulating water required for surface condensers is

$$W_c = \frac{H_2 - T_3 + 32}{T_2 - T_1} \qquad (47)$$

where T_3 = condensate temperature, and the other symbols have the same significance as before. For jet condensers T_3 becomes T_2; for surface condensers T_2 is at least 5 deg. Fahr. higher than T_2, and generally 10 or 15 deg. higher.

290. Use of dirty condensing water. For jet condensers, very dirty circulating water may be used, except that if sewage or other gas-producing

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matter is contained, the work of the dry air pump will be greatly increased. Dirty water in surface condensers causes slime deposits on the tubes, if containing grease and sewage; or it incrusts the tubes with scale, if very hard. In either case, periodic cleaning is necessary, as both deposits lower the efficiency of heat transmission.

291. Screens are usually made of iron mesh or bars, with openings the same size as condenser tubes or ¼ in. smaller; these screens are set in frames, and operate in slides for cleaning purposes. Small metal screens enclosed in cast-iron boxes in the suction pipe are employed for small sizes and are then usually called "fish-traps." A later development is the use of moving self-cleaning screens, either arranged drum fashion like a stone screen, or like a chain grate set on edge. **The velocity through screens** should not exceed 4 to 5 ft. per sec.

292. Pumps. Circulating-water pumps in modern plants are always centrifugal or propeller types, especially since the advance of the small steam turbine. **Wet vacuum pumps** handle both condensate and non-condensible gases. They are not used to any extent at present. **Dry vacuum pumps** handle non-condensible gases only. Condensate or **hot-well pumps** handle the condensate only. The separate pumps are much more efficient than the combined wet-vacuum pump. The hot well-pump is usually a one-stage or two-stage centrifugal. The dry-vacuum pump may be a reciprocating compressor specially designed for tightness and small clearance, or a hydraulic device using a form of centrifugal pump and water jets to entrain the air, such as the Le Blanc pump.

293. Power required for auxiliaries. The circulating pump, if a reciprocating dry-vacuum pump is used, requires 85 per cent. to 90 per cent. of the total h.p. for condenser auxiliaries; the condensate and dry-vacuum pumps, 5 to 7 per cent. each. The total h.p. at 27 in. to 28 in. vacuum is about 2 to 2½ per cent. of the main unit, for reciprocating main engine; 3 to 3.5 per cent. at 28 to 29 in. vacuum for turbine plants.

294. The steam demand of all condenser auxiliaries, using engine-driven circulator, is 3 to 5 per cent. of the total; for direct turbine-driven circulator, 5 to 9 per cent.; for latest type geared turbine-driven circulator, 4 to 6 per cent. The water rate of turbines used for hot-well pumps is 50 to 60 lb. per b.h.p.-hr.; for low-speed direct-connected turbines for circulators, 35 to 45 lb.; for geared high-speed turbines, 29 to 35 lb.

295. Recent High Vacuum Results with Large Surface Condensers

Plant	Surface, sq. ft.	Water per lb., hr.	Hot well temp., deg fahr.	Circ. water		Vacuum 30-in. Bar.	Ratio sq. ft. kw.
				In deg. fahr.	Out deg. fahr.		
Interborough 59th St.....	25,000	237,480	71.2	37.7	57.3	28.50	1.67
	25,000	182,508	53.2	33.3	47.6	29.15	1.67
	25,000	164,945	85.5	72.5	86.0	28.55	1.67
Marion, P. S. E. Co.....	20,000	128,000	78	60.0	73.5	29.1	2.00
United El. Lt. & Power.....	25,000	.....	71	58	68	29.0	1.67
Boston Elevated.....	28,000	182,000	74.5	64.0	74.0	29.07	2.00
	28,000	120,000	73.0	64.5	71.5	29.06	2.00
Illinois Steel..	25,000	196,000	90.6	73.4	86.1	28.25	.....
	25,000	210,000	90.3	73.4	86.9	28.3	.....
	25,000	91,000	83.3	73.6	80.0	28.8	.....

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296. Hydraulic dry-vacuum pumps take from 6 to 12 times as much power as the reciprocating types; but this is relatively unimportant if the exhaust steam is usable in the feed-water heaters.

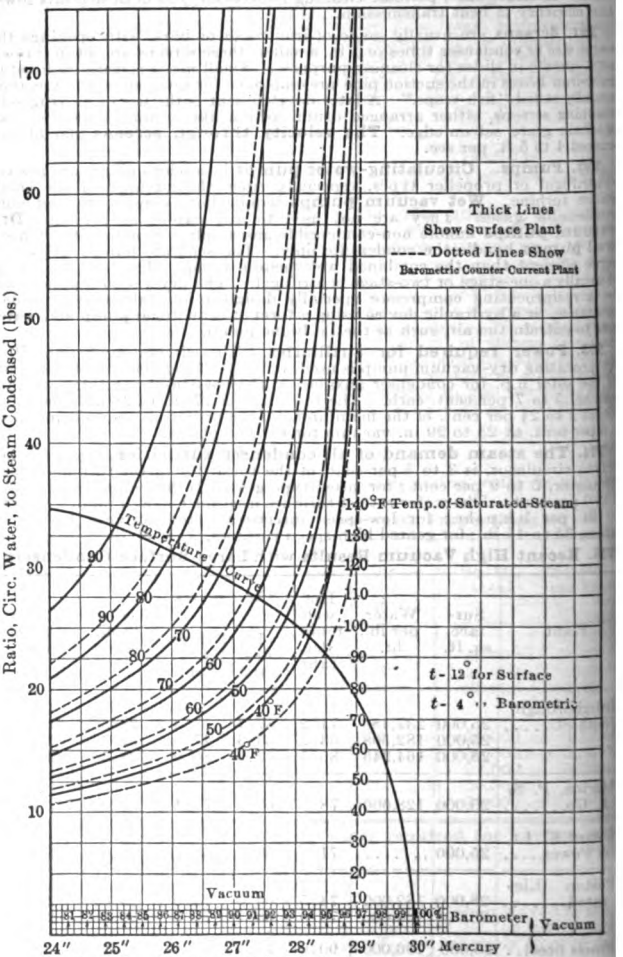


FIG. 38.—Vacuums and circulating-water temperatures.

297. The obtainable vacuum (Fig. 38) depends chiefly upon the temperature of condensing water. The actual results obtained may be less than this due to air leakage or dirty tubes.

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296. Cooling towers are employed where condensing water cannot be obtained in sufficient quantity for complete rejection of discharge. The circulating water is broken up into spray or thin sheets and falls through a current of air. The air in becoming warmer, takes up heat from the water; evaporation also takes place and tends to saturate the air. This **evaporation** is from 0.80 to 0.95 lb. per lb. of steam exhaust to the condensers, exclusive of the spray loss in water actually carried away mechanically in the air current. The distance between spray outlets and tank under the tower is usually about 25 ft. so that this head, plus friction in additional piping, must be added to the total pump head. The towers are 50 ft. to 80 ft. high for natural draft; but may be shorter if a forced draft fan is used, provided the rain from the tower is not objectionable. The ground area required is 1 sq. ft. per 20 lb. steam condensed per hr. approximately. The circulating water required is 60 gal. per sq. ft. of ground area, cooled from 95 deg. to 75 deg., which is average performance. The heat transmission to air per sq. ft. of cooling surface in the lattice work or screens runs from 350 to 850 B.t.u. per hr. The circulating water required is 25 to 30 lb. per sq. ft. per hr. The work of the circulating water pump is practically double that of the ordinary installation without towers, or 6 to 8 per cent. of the h.p. of the main unit. If forced draft is used, the fan requires 0.3 per cent. to 0.5 per cent. of the h.p. of the main unit.

299. The operation of condensing equipment becomes very simple with turbine-driven auxiliaries, as these require almost no attention. Depending on the water, condenser tubes should be cleaned from once a week to once a month; brushing the tubes may be necessary. All joints should be very carefully made and maintained tight; shellacing or painting is of great assistance in this respect. The ferrules of the tube ends need taking up from time to time, as the packing shrinks, or as the vibration loosens the ferrules.

300. Starting. The circulator should always be started first, so as to keep the tubes cool at all times when steam may come in contact with them; as soon as the circulator is running, the main unit may be started, and the hot-well pump. Whenever the vacuum is desired, the vacuum breaker valve may be closed and the dry-vacuum pump started.

301. Shutting down: shut off the main unit, break the vacuum with the breaker-valve, shut down the dry air-pump, then the hot-well pump, and lastly, the circulating water pump.

302. The piping should be so arranged that air can be removed from the highest point of the circulating water system; otherwise, air might accumulate and prevent water from entering part of the tubes, besides breaking the siphon. The discharge pipe should be submerged in the discharge tunnel or well, so as to have an inverted siphon, not to exceed 25 ft. head; this reduces the circulating pump head to friction and velocity only.

303. The cost of condensing equipment complete, including pumps, barometric type is from \$0.35 to \$0.55 per lb., average \$0.45; cost per kw. of main unit, \$1.95 to \$4.00, average \$2.80 for moderate and large size units. For very small units the cost may go up to \$8.00 or \$10.00 per kw. Jet condensers cost from \$2.70 to \$4.00 per kw., average \$3.45, for moderate and large sizes; \$6.00 to \$9.00 for small units. The figures assume 26 in. or 27 in. vacuum and are based on normal kw. rating. Surface condensers, 28 in. to 29 in. vacuum, cost per kw. of main unit from \$4.80 to \$8.90 average \$6.50; this is based on maximum rating of units and applies to large sizes. Small surface condensers cost from \$7.50 to \$20.00 per kw. Cooling towers, \$6.50 to \$12.00, average \$9.00 per kw. rating of units attached (1920).

FEED-WATER HEATERS

304. The heat transfer in closed feed-water heaters is exactly the same as in surface condensers; that in open heaters, the same as in jet condensers, as covered in Par. **285** to **289**. The feed-water heater is merely a condenser operated at atmospheric pressure, with boiler feed-water for condensing water.

305. The open heater is much like a jet condenser in general arrangement, but is usually a rectangular box, or cylindrical tank large enough to

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provide a little storage capacity for feed water, as the boiler feed pumps usually draw direct from the heater.

306. The closed heater is usually built much like a surface condenser and is then known as the straight-tube type. In some makes the tubes are corrugated, in others coiled, or with a single U-bend; or an expansion joint is placed in the shell; in these cases the tubes are expanded fast in the tube sheets. In a few types, a floating head is used with straight tubes.

307. The water velocities employed in closed feed-water heaters are usually slower than for surface condenser practice, so that the value of the transmission coefficient is reduced. An average figure is 300 B.t.u. per deg. mean temp. difference per sq. ft. per hr.

308. The mean temperature difference given by the arithmetic formula is close enough.

$$t_m = t_s - \left(\frac{t_2 + t_1}{2}\right) \tag{48}$$

where t_s = temperature of exhaust steam at exhaust pressure (usually 212 to 214 deg.), t_2 = temperature of heater discharge water, and t_1 = temperature of heater inlet water.

309. Temperature rise. If a given quantity of exhaust steam is available, the resulting temperature rise in a closed heater may be found as follows:

$$(t_2 - t_1) = \frac{w_s(H_s - q_2)}{W} \tag{49}$$

where W = feed water in lb. per hr., w_s = exhaust steam in lb. per hr., H_s = total heat of exhaust steam per lb. (usually 1,150 B.t.u.), q_2 = heat of the liquid (condensed steam), at the temperature leaving the heater (t_2), usually 212 deg., t_1 = temperature of feed water at heater inlet, and t_2 = temperature of feed water at heater discharge. For all ordinary cases, $H_s - q_2 = 970$. t_2 cannot be higher than 208 deg. fahr., if exhaust steam at 212 deg. is employed. If the value of t_2, as found above, exceeds this, it indicates that there is excess exhaust steam. Eq. 56 can be transposed to solve for w_s, if the amount of exhaust steam to heat the feed water to 208 deg. is desired.

310. Temperatures Obtainable in Open Feed Water Heater
(Temperature of steam, 212 degrees F.)
Initial Temperature of Feed Water, Degrees F.

Per cent. of total steam used by auxiliaries.	40	50	60	70	80	90	100	110	120	130
2	60.1	69.9	79.7	89.5	94.4	109.2	119.0	128.8	138.7	148.5
3	69.9	79.6	89.3	90.1	108.8	118.6	128.3	138.0	147.8	157.5
4	79.5	89.1	98.8	108.5	118.1	127.8	137.4	147.1	156.7	166.4
5	89.0	98.5	108.1	117.7	127.2	136.8	146.4	155.9	165.5	175.1
6	98.3	107.7	117.2	126.7	136.2	145.7	155.2	164.7	174.2	183.6
7	107.4	116.8	126.2	135.6	145.0	154.4	163.8	173.2	182.5	192.1
8	116.4	125.7	135.0	144.4	153.7	163.0	172.4	181.8	191.0	200.3
9	125.2	134.5	143.7	153.0	162.2	171.5	180.7	190.0	199.2	208.5
10	133.3	143.1	152.3	161.4	170.6	179.8	189.0	198.1	207.3	212.0
11	142.5	151.6	160.7	169.7	178.9	188.2	197.0	206.2	212.0*	212.0*
12	150.9	159.9	168.9	177.9	187.0	196.0	205.0	212.0*	212.0*	212.0*

311. The surface required in closed heaters is given by

$$A = \frac{W(t_2 - t_1)}{U t_m} \tag{50}$$

where $U = 300$ and A = area of tube surface in sq. ft.; the other symbols are as given in Par. **309.**

312. Heaters are rated in h.p. One h.p. equals 30 lb. of exhaust steam per hr. This unit ought to be abandoned and million B.t.u. transfer capacity used instead.

* All of the steam not condensed.

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313. The volume required in open heaters is given by

$$V = \frac{HP}{a} \qquad (51)$$

where V = volume in cu. ft., $a = 2.15$ for muddy water, $a = 6$ for slightly muddy water, and $a = 8$ for clean water.

314. Operation. The operation of closed heaters is somewhat more expensive than open heaters; the tube packings require attention and the tubes must be cleaned of scale, if this forms. In heaters with corrugated or bent tubes, cleaning is practically impossible. The advantage of the closed heater is the elimination of oil from the feed water, but with the use of turbine-driven auxiliaries, this advantage disappears, as there is no oil in the exhaust steam. In open heaters, the cast-iron trays over which the feed water spills, are readily removable for cleaning. If an open heater is used on oily exhaust, some means of oil elimination must be used, sometimes supplemented by a filter in the body of the heater.

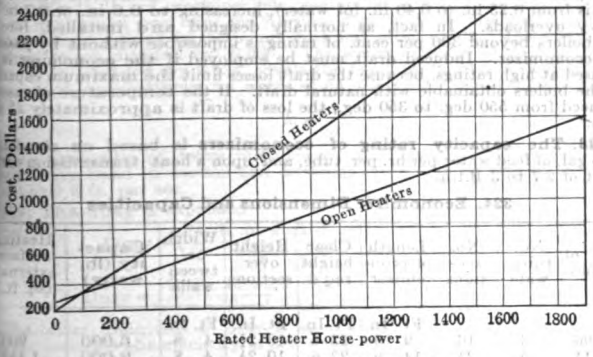


FIG. 39.—Cost of feed-water heaters.

315. Connection to feed pump. Closed heaters may be either the suction or the discharge side of the feed pump; open heaters, only on the suction side. Either type when on the suction side of the pump, must be above it.

316. The cost of heaters is given in Fig. 39.

ECONOMIZERS

317. The laws of heat transfer for economizers are the same as for surface condensers and closed water heaters. But the substitution of a gas for the steam increases the resistance enormously, and the value of the transmission coefficient is much lower and is very uncertain in value.

318. Types. There are two types: the **staggered tube** and the **non-staggered tube.** In both types the tubes are arranged in vertical rows attached to headers at top and bottom of each row, perpendicular to the gas flow. The staggered arrangement serves to break up the gas stream thoroughly. The tubes are always of cast iron and are usually 4½ in. diameter and 10 ft. long.

319. The surface required is based on empirical values, because the temperature and quantity of flue gases per lb. of coal, waterflow and condition of surfaces, introduce so many independent variables that the rational formulæ used for condensers and heaters are useless. The surface installed varies from 1.50 to 3.00 sq. ft. per rated boiler h.p. connected.

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320. The temperature rise is given by

$$X = \frac{y(T_1 - t_1)}{9.1 + \frac{5w + GCy}{2GC}} \qquad (52$$

where X = rise in temperature of feed (deg. Fahr.), T_1 = temperature flue gase entering economizer, t_1 = temperature feed water entering economize w = lb. of feed water per boiler h.p. per hr., G = lb. flue gas per lb. of combu tible (average, 20), C = lb. of coal per boiler h.p. per hr., and y = sq. ft. of econo mizer surface per boiler h.p. A rough method, if the temperature drop o flue gases is known, is to take 0.5 deg. rise in feed water for every deg. dro in flue gases.

321. The feed water enters the bottom headers by a connecting mai and is collected from the top headers by another main, placed at the op posite end of the headers, so that the tubes form equal parallel paths.

322. The draft loss through economizers varies with the velocity of th gases, as in the boiler. At normal full load on the connected boilers th loss is from 0.25 in. to 0.40 in. (of water), increasing to 0.6 in. or 0.7 in. a heavy overloads. In fact, as normally designed and installed, forcin the boilers beyond 300 per cent. of rating is impossible without by-passin the economizer. Induced draft must be employed if the economizer is t be used at high ratings, because the draft losses limit the maximum capacit of the boilers obtainable with natural draft. If the temperature of gases reduced from 550 deg. to 350 deg., the loss of draft is approximately 25 pe cent.

323. The capacity rating of economizers is based on circulatin 6.25 gal. of feed water per hr. per tube, and upon a heat transmission coeff cient of 2.7 to 3 B.t.u.

324. Economizer Dimensions and Capacities

No. of tubes	No. tubes wide	No. sections	Length of economizer	Clear height req'd	Height over sections	Width between walls	Capacity (lb. water)	Heating surface external (sq. ft.)
			Ft. In.	Ft. In.	Ft. In.	Ft. In.		
96	6	16	9 8	23 6	10 2½	4 8	6,000	960
144	6	24	14 6	23 6	10 2½	4 8	9,000	1,440
192	6	32	19 4	23 6	10 2½	4 8	12,000	1,920
240	6	40	24 2	23 6	10 2½	4 8	15,000	2,400
128	8	16	9 8	23 6	10 2½	6 0	8,000	1,280
256	8	32	19 4	23 6	10 2½	6 0	16,000	2,560
384	8	48	29 0	23 6	10 2½	6 0	24,000	3,840
512	8	64	38 8	23 6	10 2½	6 0	32,000	5,120
576	8	72	43 6	23 6	10 2½	6 0	36,000	5,760
160	10	16	9 8	23 6	10 2½	7 4	10,000	1,600
320	10	32	19 4	23 6	10 2½	7 4	20,000	3,200
480	10	48	29 0	23 6	10 2½	7 4	30,000	4,800
640	10	64	38 8	23 6	10 2½	7 4	40,000	6,400
800	10	80	48 4	23 6	10 2½	7 4	50,000	8,000

Any other number of sections in multiples of 4, from 8 to 80, can be em ployed, giving proportionate dimensions.

325. Accumulation of soot occurs upon the tubes, and the "sweating" which takes place at low feed temperatures tends to catch and hold the soo firmly. **Continuous scraping** of the tubes is employed to overcome th difficulty. The cast-iron scrapers are driven slowly up and down th tubes in pairs, requiring about 1 h.p. to every 300 or 350 boiler h.p. connecte to the economizer. There is a friction rig on each scraper drive so that any solid obstruction stops one scraper, it will neither break the scrape nor interfere with the others.

326. The operation of economizers requires attendance for the scraper cleaning the inside of the tubes, and cleaning soot and fine cinder from th

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bottom of the economiser chamber. The first item is small, as the drive is usually by motor and the mechanism is very slow moving; the second depends on the feed water and should occur with less frequency than in the boilers; the last depends on the rate of driving and the coal, varying from once a month to once in four months.

327. The cost of economisers averages about $15.00 per tube, installed. The tubes are usually 4½ in. by 10 ft.; cast iron is employed throughout, since of the low rate of heat interchange, any other material would be too expensive. From the point of view of increased economy and the cost of securing it, the economiser is the least desirable of all auxiliaries. In many cases it cannot be made to pay; this is generally true if it saves less than 10 per cent. If it saves over 10 per cent., there is reason to conclude that the cost of the plant is being very badly operated.

PUMPS

328. The work done by a pump is given by

$$W = wh \tag{53}$$

where W = ft.-lb. of work per min. performed in lifting the water, w = lb. of water pumped per min. and h = sum of suction lift, discharge head and velocity head gained in the pump inlet and outlet, in ft. The water h.p. is equal to wh divided by 33,000. The water pressure, or suction, in lb. per sq. in. divided by 0.434 equals the head in ft. at the discharge, or the suction, respectively, for water at 62 deg. fahr. The velocity head is

$$h_v = \frac{v^2}{2g} \tag{54}$$

where v = velocity of water in ft. per sec. and $2g = 64.35$. For most cases, the velocity head in suction and discharge pipes may be disregarded, as it is not over 8 ft. per sec.

329. The duty is expressed

$$\text{Duty} = \left(\frac{\text{ft.-lb. of work done on water}}{\text{weight of dry steam}}\right)1{,}000 \tag{55}$$

or

$$\text{Duty} = \left(\frac{\text{ft.-lb. of work done on water}}{\text{Total B.t.u. used}}\right)1{,}000{,}000 \tag{56}$$

The latter definition of duty is more satisfactory than the first; duty always includes the efficiency of the steam end, as well as the water end.

330. Pumps are broadly classed in four types—reciprocating, centrifugal and turbine, rotary, and jet pumps. The **reciprocating type** can be subdivided into direct-acting, flywheel and power pumps. **The direct-acting type** has steam and water cylinders on a common piston rod, and no flywheel; the valve mechanism for the steam cylinder is actuated direct from the rod by tappets. This type may be single-cylinder, or duplex, and the steam cylinders may be simple, compound or triple expansion. **The duplex simple pump** is the most rugged and reliable of all. Outside-packed plungers are the most desirable, as the packing on the plunger is adjustable while running and the amount of leakage can be seen. **Flywheel pumps** are similar to the direct-acting type, except that a flywheel is added and the steam valve is gear driven from the shaft as in a steam engine. Pumping engines are a development of this type. **Power pumps** are fitted with one or more cylinders, driven from a crank shaft and belted or geared to the source of power. When three cylinders with cranks at 120 deg. are used, the pump is known as a triplex; this type is very frequently gear-driven from a motor or an internal combustion engine.

331. Centrifugal pumps are those in which pressure and flow is produced by a rotating impeller, which gives the water entering it an increase in velocity; this velocity is converted into pressure by a suitable whirlpool chamber or diffuser. **The obtainable head** is proportional to the square of the peripheral velocity of the impeller; this velocity is subject to practical limitations, so that 150 to 200 ft. head is about the upper limit desirable in a single impeller. For higher heads, such as boiler feeding, the pumps are made two, three or more stages, consisting merely of single impellers connected in series in a single casing.

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332. Rotary pumps are very little used in power-station service; the commonest types are the bi-lobular type, and the gear pump. Neither has very good efficiency.

333. Screw or propeller pumps, while not strictly centrifugal, create pressure in the same manner, and are usually considered in the same class.

334. Jet pumps are covered in Par. **345** to **353.**

335. The characteristic curve of a centrifugal pump is necessary for determining its behavior. The capacity of a reciprocating or a rotary pump varies directly with the speed and is substantially independent of the pressure. The usual graphs are between capacity and efficiency, and capacity and head. Fig. 40 gives results for a 6-in. single-stage pump. Pumps for similar service, but different sizes, will have about the same characteristics, the efficiency increasing slightly with the size.

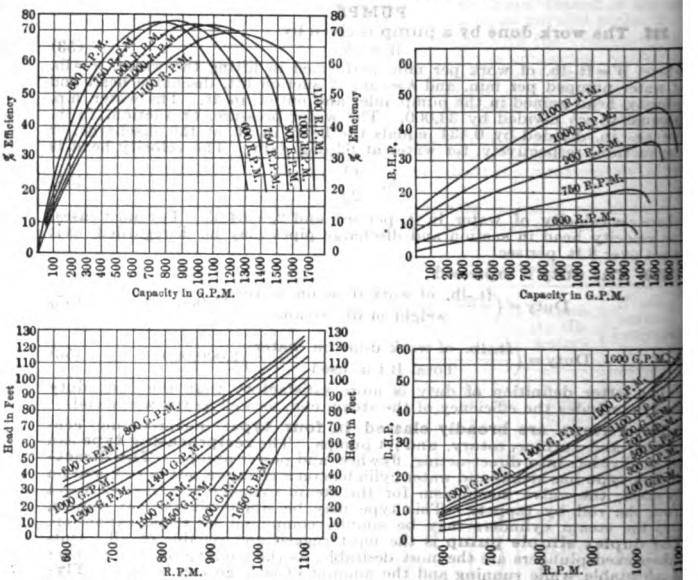


FIG. 40.—Characteristics of a 6-in. single-stage centrifugal pump.

336. Boiler feed pumps are usually the duplex outside-packed plunger type, or the three-stage or four-stage centrifugal. Occasional installations of motor-driven triplex pumps are made, but are undesirable. The principal feature required is reliability, which at once gives the steam-driven apparatus the precedence. The duplex direct-acting type was, until recently, almost exclusively used, but is now being replaced by the turbine-driven centrifugal. Fig. 40 shows that the pump speed is increased slightly as the delivery increases; this gives a more nearly constant head and a better efficiency with the variable loads.

337. Pressure regulators are employed to control the speed of all direct-acting boiler feed pumps and also, in most cases, for the centrifugal types.

338. The efficiency of direct-acting steam simplex and duplex pumps is low mechanically and thermally. The mechanical efficiency

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(water h.p./indicated h.p.) varies from 0.50 in small pumps to 0.85. The water rates are very high, both on account of the low speed and the absence of expansion.

339. Performance test of boiler feed pump. The following test of economy of Marsh pumps was made at Armour Institute of Technology; size 12×7¼×12 in.; steam actuated valve gear; initial pressure 100 lb. gage; back pressure 2 lb. gage.

Number of strokes	Pump h.p.	Steam per indicated h.p.-hour	Number strokes	Pump h.p.	Steam per indicated h.p.-hour
10	1.0	400	60	6.4	105
20	2.0	210	70	7.6	101
30	3.0	168	80	8.8	100
40	4.1	130	90	10.0	99
50	5.2	118	100	11.3	99

(G. F. GEBHARDT)

340. The mechanical efficiency of geared triplex pumps is high, running up to 0.82 for motor-driven and high-speed pumps; the low-speed geared pumps reach 0.70.

341. The efficiency of centrifugal pumps depends on the size and number of stages. De Laval gives the following data for volute pumps.

Capacity	Efficiency	Capacity	Efficiency
75– 250 g.p.m.	55 to 65	3,000– 6,000	73 to 75
250– 900	70	6,000–10,000	75 to 78
900–3,000	70 to 73	10,000–up	75 to 85

The maximum efficiency of two-stage pumps is about 70 to 75 per cent of three-stage and four-stage pumps, about 60 to 68 per cent. These values apply to turbine speeds, as in turbine drive. The efficiency of a volute pump is usually stated at the proper speed for the head. At turbine speeds and under low head, the efficiency drops about 20 to 25 per cent; this is the case for turbine-driven circulating pumps, in which the speed is too high for efficient low-head pumping and still too low for efficient turbine water rates. The latest solution is a reversion to the de Laval geared drive, using helical gears.

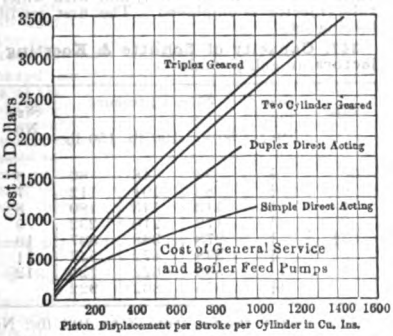


FIG. 41.—Costs of reciprocating pumps.

342. Costs are given in Fig. 41 for simplex and duplex pumps, and for triplex and two-cylinder geared power pumps. All costs are given in terms of displacement. The cost of large geared double-acting pumps is from $2.15 to $6.50 per cu. in. of displacement. The cost of single-stage centrifugal pumps is from $1.10 to $1.80 per gal. per min. of capacity. Multi-stage centrifugal pumps cost from $6.50 to $11.00 per gal. per min. of capacity (1920).

343. The usual piston speeds at which capacity is calculated for piston pumps, are from 100 to 200 ft. per min. for strokes below 12 in. and 100 ft. per min. for all strokes longer than 12 in.

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344. Operation. The direct-acting simplex or duplex steam pum requires almost no attention except occasional packing of glands and lubr cating. When controlled by a **pressure governor,** the delivery is suite to the demand. It will run on water as well as steam, and little care need b taken to supply it with dry steam. The geared triplex type requires mo careful attention on account of the additional parts to be lubricated; motor-driven, it must be provided with a suitable speed control, or it canno be used on variable load. Piston and rotary pumps must always be provide with **relief valves** in the discharge, as they are positive in action and wi produce excessive pressures if the discharge is restricted.

Centrifugal pumps cannot discharge under a higher head than that corr sponding to the speed, therefore no relief is needed; the reason for using pre sure governors with turbine-driven centrifugal boiler feed pumps is to reduc the speed in proportion to the delivery in order to keep up the efficiency Centrifugal pumps are generally ring oiled and therefore require very litt attention. The packing of the glands where the shaft leaves the pump casin is usually water-sealed; for this purpose a clean cool water should be pr vided. All centrifugal pumps must be primed before they will operate, an if no vacuum apparatus is provided, a foot-valve on the suction pipe must b used to prevent the water draining out of the pump on shutting down. discharge valve must be provided, to be closed when priming, until th pump develops pressure.

JET PUMPS

345. Jet pumps operate by means of the kinetic energy of a rapidl moving stream of fluid. In those operated by steam, a jet of the high-pre sure steam issues into a chamber at approximately atmospheric pressure a little below, and there strikes the supply of water to be pumped. Th impact of the steam transfers momentum to the water, which, together with th condensed steam, is hurled into a second nozzle which converts the kinet energy of the mass into pressure and the stream enters the pressure chamb through a check valve. Since the water pumped must condense the stea used, it has a limitation in temperature, or the injector will fail to work.

346. Injectors are used for boiler feeding. For low and moderate pre sures a single steam tube is used, both for lifting the water and forcing into the boiler. But for heavier pressures and greater flexibility in handlin variable quantities of water, and with wider range of pressure, the doubl tube injector is employed. The first jet lifts the water to the second, forcing jet.

347. Capacity of Schütte & Koerting double-tube boiler-feed in jectors, in gal. per minute.

Size No.	Size pipe (in.)	Steam pressure			Size No.	Size pipe (in.)	Steam pressure		
		50 lb.	100 lb.	150 lb.			50 lb.	100 lb.	150 lb
00	¼	33	48	60	6	1¼	825	990	1,12
0	¼	83	101	112	7	1½	1,072	1,372	1,61
1	⅜	112	143	180	8	1½	1,388	1,800	2,11
2	⅜	172	210	232	9	2	1,688	2,100	2,47
3	¼	278	338	397	10	2	2,025	2,438	2,85
3½	¼	398	472	547	11	2–2½	2,530	3,050	3,51
4	1	533	622	720	12	2½	3,000	3,638	4,25
5	1¼	675	802	922					

The weight ranges from 3 to 108 lb.; No. 2 weighs 10 lb. and No. weighs 20 lb.

348. Ejectors are either single-tube jet pumps, or direct-pressure pum in which steam, or air, is admitted directly into a chamber filled by gravi with the liquid to be pumped. The pressure closes the inlet check valve a forces the water or other liquid out; when the chamber is emptied, a flo therein drops and relieves the pressure, allowing the chamber to fill agai As the liquid reaches the top, the float rises and readmits pressure. Th Shone and Albany traps are examples.

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349. **Inspirators** are injectors of the double-tube type (Par. 346).

350. **Siphons**, so called, are single-tube jet pumps used for lifting only. , steam, or high-pressure water may be the motive force. They are not d for forcing against more than a few feet head.

351. **Pulsometers** comprise another form of direct-pressure pump like ejector, and operate in much the same manner. The operating steam is ndensed by the cold-water chamber and, in collapsing to water, draws chamber full of water and operates a ball valve to admit steam again. ere are always two chambers, one filling and one discharging, operated by single ball valve. The pulsometer, therefore, can lift water by suction, ereas the pressure-type ejector must be primed by gravity.

352. **Efficiency.** If the mechanical efficiency alone is considered, all pumps are very inefficient, being more wasteful of steam than the direct- ng steam pump. But thermally considered, the steam injector is nearly per cent. efficient, since the heat of the exhaust steam is returned in the l water. The siphon and the pulsometer are convenient for temporary and for drainage of pits under conditions adverse to the use of machinery.

353. **The cost of these classes** varies so widely that representative figures hardly be given, $3.00 to $8.00 per 100 g.p.m. capacity covers most cases.

PIPING

354. **The requirements of piping** are: (a) tightness against leakage; reasonably small pressure loss through friction; (c) suitable provision for nge of length through change of temperature of the fluid contained; reasonably small loss of heat by radiation if the fluid is hot, and intended e kept so. Most of these requirements increase the first cost; a balance t therefore be found beyond which it does not pay to carry refinements.

355. **The flow of steam** is expressed by Unwin as

$$W = 87.5\left\{\frac{\gamma P d^5}{L\left(1+\frac{3.6}{d}\right)}\right\}^{\frac{1}{2}} \tag{57}$$

$$P = 0.0001306\left(\frac{W^2 L\left(1+\frac{3.6}{d}\right)}{\gamma d^5}\right) \tag{58}$$

re W = lb. steam flowing per min., L = pipe length in ft., d = inside eter of pipe in in., γ = mean density of steam at pressures in the pipe P = pressure drop in. lb. per sq. in. Babcock's formula differs only in constant (87.0). Carpenter's is the same as Unwin's.

356. **Steam flow chart, based on Unwin's formula.** This chart . 41a) gives accurate results of the formula, and was prepared by Prof. L. Durand. An example will illustrate its use: 100 lb. steam pressure, ft. of pipe line, 4 lb. total pressure-drop. The drop per hundred feet 5 lb. Starting at 100 lb. mark, drop down vertically to diagonal line ked 4 in., traverse horisontally to left to the diagonal marked 0.5 and off weight of flow per minute vertically, 73 lb. in this case. It will be d that the range of pipe sizes is not consecutive on the chart; this is use the chart "repeats," and the lines for each of the four scales lie the same area.

357. **The flow of water in long pipes** is given by Church as

$$Q = 3.15\sqrt{\frac{d^5 h}{fl}} \tag{59}$$

re Q = cu ft. per sec., d = diameter pipe in ft., h = head of water in ft., efficient of friction and l = length of pipe in ft.
or pipe under 500 diameters in length,

$$Q = 6.3\sqrt{\frac{d^5 h}{(1+0.5)d+4fl}} \tag{60}$$

358. **The loss of head due to friction** is given by Weisbach as

$$H = \left(0.0144+\frac{0.01716}{\sqrt{V}}\right)\frac{V^2}{5.367d^1} \tag{61}$$

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where H = friction head in ft., V = velocity of water in ft. per sec. and d = diameter of pipe in inches.

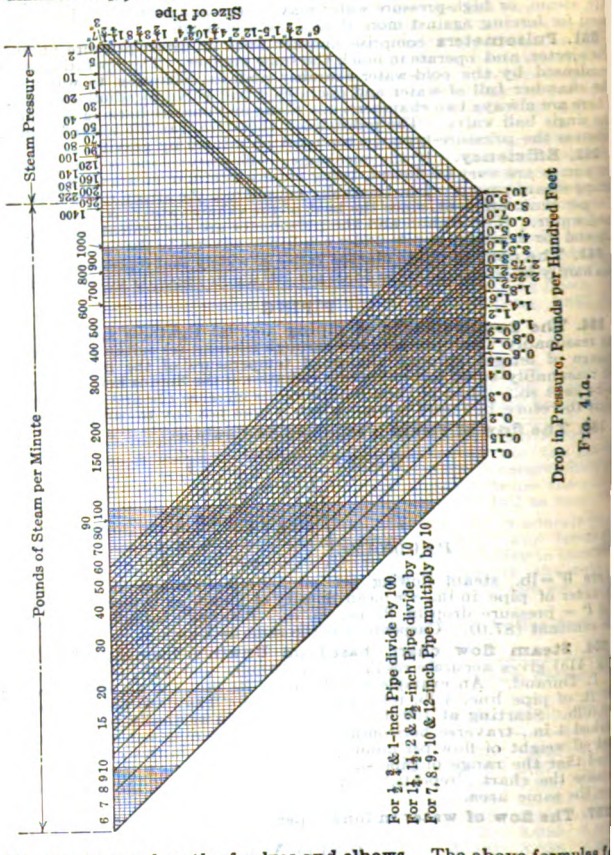


FIG. 41a.

359. Equivalent length of valves and elbows. The above formulas f steam and water (Par. **357** and **358**) apply to straight pipes. Valves a elbows may be figured as equivalent to lengths of straight pipe as fol for steam,

$$L = \frac{6.33\,d}{\left(1 + \frac{3.6}{d}\right)} \text{ for each 90 deg. ell}$$

$$L = \frac{9.5d}{\left(1 + \frac{3.6}{d}\right)} \text{ for each globe and angle valve,}$$

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where L = equivalent length of straight pipe in ft., and d = diam. of pipe in in. Gate valves are not considered. **For water,**

$$H = C\left(\frac{V^2}{2g}\right) \qquad (64)$$

where C = coefficient, 0.182 for 45 deg. ells, 0.98 for 90 deg. ells, 0.182 for gate valves, 1.91 for globe valves, and 2.94 for angle globe valves.

360. The principal piping systems are: high-pressure steam; exhaust or low-pressure steam; hot, cold and circulating water piping; and oil piping.

361. High-pressure steam piping is made chiefly of steel pipe with cast-iron fittings, if saturated steam is used; if superheat is employed, cast-steel fittings and valves must be used, as cast-iron will not stand the temperature. For any pressure up to 125 lb. per sq. in. **standard fittings** are used; above 125 lb. **extra heavy fittings. Screwed** fittings should not be used above 6-in. pipe sizes; all larger material should be **flanged.**

362. On exhaust lines, standard weight pipe and fittings are usually employed; for very large sizes, however, special light-weight fittings may be used to save weight and first cost. Screwed pipe may be used up to 8-in. pipe sizes, but flanged fittings are preferable for everything over 4 in. Spiral riveted **galvanised** pipe may be used in place of standard pipe, as it is very much lighter and perfectly suitable for moderate pressures. It cannot be used on vacuum work.

363. Hot and cold water mains are made up the same as live steam lines; except that in some cases cast-iron pipe as well as fittings are employed throughout on high-pressure hot-water service, to minimize corrosion effects. No cast-steel fittings are necessary. For circulating water lines, galvanised spiral riveted pipe is useful for fresh water, but cast-iron pipe is generally used throughout for salt water and is preferable even for fresh water.

364. Oil systems were generally installed in brass pipe and fittings on the supply to engines; but it has been found that steel pipe, if well cleaned, is perfectly satisfactory for the service. There is little excuse for the use of brass piping except for appearance, on gage fittings, or for some special service where corrosion would be fatal.

365. There are four principal systems of piping arrangements: individual supply; ring; header; and unit (Fig. 42). The **individual** supply is really not a system, but the lack of it, and should not be employed.

366. The ring system is a development of the duplicate header; all supply lines tap in on one side of the ring, all demand lines on the other; by means of sectionalizing valves in the main, any section may be isolated without interfering with the rest of the plant.

367. In the header system, all supply and demand lines tap to one large main; so that if any section is cut out, it must interfere to some extent with the operation of the plant. This feature may not be serious; but for large power stations it is undesirable.

368. Unit system. The modern tendency is to revert to the unit system. This is the individual supply system—each group of boilers supplying its own turbine, but the units are tied together by equaliser pipes; so that there is really a header of diminished capacity between the units. Fig. 42 gives a typical example.

369. Expansion in steel and cast-iron pipe may be taken as 0.9 in. per 100 deg. temperature difference from atmosphere, per 100 ft. of pipe under average conditions. **Expansion joints** should be provided every 50 ft. of straight steam main; every 75 or 100 ft. will do for water or exhaust steam. See Sec. 4, for coefficients of expansion of piping materials.

370. The slip expansion joint is useful for water service and exhaust steam at atmospheric pressure. It should never be used for high-pressure steam or vacuum; its capacity can be anything up to 9 in. or 10 in. of movement.

371. The copper bellows joint is very successful for low-pressure steam and vacuum work, particularly the type having only one corrugation. Its capacity however is never over 0.5 to 1 in. of expansion, and preferably not over 0.25 in. This type of joint is sometimes made up of boiler plate for high-pressure steam service.

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372. The pipe bend is the simplest and safest joint for high-pressure steam and is usually made of as large radius as can conveniently be made, taking care of from 1.5 to 2 in. of expansion per bend.

373. Avoidance of strains in fittings. Piping should always be laid out so that expansion will not bring strains upon cast-iron fittings, but upon the expansion joints, or at least upon the more flexible steel pipe.

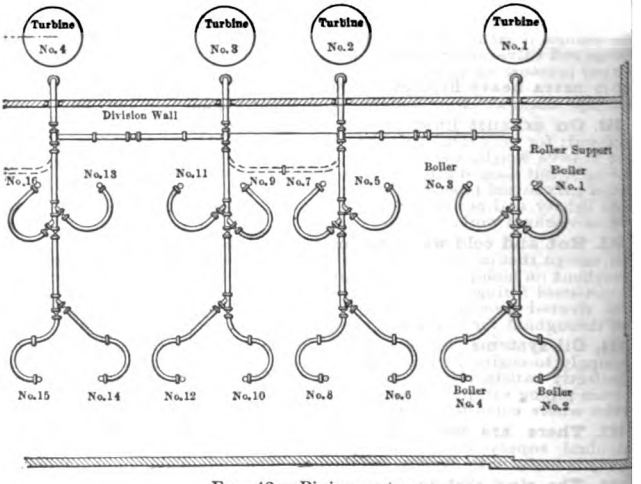


FIG. 42.—Piping systems.

374. Condensation in steam pipes is due to radiation; it occurs only i saturated steam mains, when running. All low points in the piping syste and all dead ends or pockets where water can collect, must be drained. Th usual method for high-pressure steam is to connect a steam trap at eac point to be drained and can be returned direct to the boilers, or to the fee tanks. Low-pressure steam mains are usually drained by gravity throug an inverted siphon leg, to act as a steam seal.

375. Steam traps are of four principal types: bucket, float, tilting an expansion. The bucket and tilting traps are probably the most reliabl

376. Separators are employed to remove moisture from the steam befo it is supplied to an engine. In every instance short and sudden turns a employed to throw out the moisture by centrifugal force, and a large chamb is then provided to reduce the velocity of the steam and act as a reservoir t collect and retain the water. (See Fig. 20a.)

377. Controlling valves are of three types: gate, globe and angle. Th **globe valve** is always used for stop or throttle work. The **angle valve** really a globe valve with the outlet turned through 90 deg. and is used as globe valve, usually for the stop valve on boilers. For all other steam wo the **gate valve** should be used on account of offering practically no obstru tion to steam flow. All exhaust valves should be of the gate type. F water service, gate valves should be used wherever possible. **Check valv** may be horizontal, vertical, and swing. The horizontal and vertical che valves ordinarily are built much like a globe valve, but the valve disc has stem and wheel for closing it.

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378. Relief and back-pressure valves are developed from the check alve, with a spring or lever and weight loading device, so that a definite ressure under the valve disc will lift the valve and let off pressure. Relief alves are used on the discharge of reciprocating pumps to prevent excessive ressures; also on cylinders and receivers of steam engines. Back pressure nd atmospheric relief valves are used on exhaust steam systems and con-ensers respectively. All of these types are emergency valves, to prevent amage under unusual conditions.

379. Reducing valves are usually double-seated, or balanced, valves, ith a pressure diaphragm substituted for the spring of the relief valves. his diaphragm is connected to the discharge side of the valve, and operates close the valve only when the pressure on the discharge side rises above the redetermined amount. They are used to feed high-pressure steam into w-pressure systems

380. The three principal types of pipe joint used are; screwed, flanged, nd bell and spigot. The **screwed joint** is used for all pressures and ser-ice up to 3-in. diameter of pipe, and up to 12 in. for low-pressure service. bove 3 in. in high-pressure service and 12-in low-pressure service the **anged joint** in one of its forms is used.

381. The principal methods of attaching flanges to steel pipe are: anwed flanges, peened flanges and, lately, machine expanded flanges, welded anges and lap flanges. Of these, **screwed flanges** are in common use for w-pressure work, and high-pressure work up to 100 lb. in size up to 24 in. ., or up to 150 lb. in sizes not larger than 6-in. or 8-in. diameter. It is a eap and satisfactory joint when well made.

382. A much better joint for high pressures is the lap joint, in hich the pipe is lapped over on the flange and then faced off. The **olded joint** is also satisfactory but more expensive. The new **machine-panded joint,** in which the pipe is rolled into a recess in the flange, romises well and is cheap to make: it has been used for years in marine work.

383. Gaskets for low-pressure work may be of rubber compounds or sbestos. For high-pressure steam, asbestos, and the metallic gaskets, such corrugated copper, are better.

384. Bursting pressure of standard mild steel pipe. Tests made at e Armour Institute of Technology on 5-ft. random specimens capped at oth ends gave average results as follows: 1-in., 7,730 lb. per sq. in.; 2-in., 960 lb.; 4-in., 1,750 lb.; 5-in., 2,550 lb.; 6-in., 3,200 lb.; 10-in., 1,800 lb.; 2-in., 2,500 lb. On the 4-in., 5-in., 6-in., 10-in. and 12-in. sizes failure curred at the threaded end.

385. Pipe covering is practically always justified for high-pressure steam, ld for exhaust also, if used for heating feed water. Hot feed-water pipes ould also be covered. The standard coverings are principally magnesia, sbestos and the fossil meal compounds. Moulded sectional covering can be btained for pipes up to 12-in. diameter in single (1-in.) and double (2-in. to -in.) thickness. All exhaust lines should be covered with single thickness; ll steam lines, with double thickness. Usually the covering is bought eady canvassed. For larger size pipe than 12 in., sectional blocks, about -in. × 3 in. × 18 in. are used, and wired on; then the joints are pasted ith asbestos cement and the whole is canvassed and painted. Moulded overing can be bought in shapes to fit standard fittings, such as tees and ells, ut is frequently made up from blocking and asbestos cement.

386. The radiation losses from uncovered pipe are given by

$$Q = A(T_1 - T_2)U \qquad (65)$$

here A = sq. ft. of radiating surface, T_1 = temperature of steam within the pe, T_2 = temperature of air outside, and U = transmission coefficient = B.t.u. per sq. ft. per hr. per degree of temperature difference.

r 1-in. magnesia, 85 per cent., $U = 0.4 - 0.5$ (66)

r 1.5-in. magnesia, 85 per cent., $U = 0.25 - 0.3$ (67)

In a modern plant, with properly covered piping the actual radiation loss om pipe alone should not exceed 1 per cent. of the total heat of steam pass-g through at full load.

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387. Tests of Relative Efficiencies of Steam-pipe Coverings

Kind of covering	Size of pipe, inches	Thickness of covering, in.	B.t.u. per sq. ft. per deg. diff. of temp.	Per cent. heat lost	Authority
Bare pipe	.....	.....	2.7	100	.....
Hair felt	2	0.96	0.387	14.3	Jacobus
Remant	2	0.88	0.434	16.1	Jacobus
Solid cork	2	1.20	0.427	15.8	Stott
Magnesia	2	1.16	0.439	16.3	Stott
Magnesia	4	1.12	0.465	17.2	Norton
Asbestos sponge felted	10	1.63	0.280	10.4	Barrus
Asbestos sponge felted	2	1.21	0.490	18.1	Barrus
Manville sectional	4	1.25	0.453	16.8	Norton
Manville sectional	2	1.31	0.572	21.2	Paulding
Asbestos air cell	4	1.12	0.525	19.4	Norton
Asbestos air cell	2	0.96	0.716	26.5	Jacobus
Asbestos fire felt	8	1.30	0.502	18.6	Brill
Asbestos fire felt	2	1.00	0.721	26.7	Paulding

(Abstracted from "Book of Standards," National Tube Co., Pittsburg Pa.)

388. Exhaust heads comprise a form of separator in which the entrain moisture in atmospheric exhaust is removed so that the issuing steam may t be a nuisance to the neighborhood, or an injury to the roof. They oper on the same centrifugal principle as separators.

389. Blow-off valves and piping, being subject to rapid variation fr low to high temperature, must be carefully designed for expansion. As so scale and rust flakes must be passed, the turns should be easy, and all co nections between individual boilers and mains should be by 45-deg. later instead of tees.

390. The installation of piping should be done with great care to p vide good alignment. Pipe joints can be made when piping is considera out of line, as the lines are more or less flexible, but satisfactory joints s service cannot be expected. For **high-pressure** work, it is unsafe to str the pipe in order to joint it. It is therefore good practice to arrange conn tions for flexibility, in case of variation from drawing dimensions; or bett to leave certain pieces of pipe called **fillers**, to be cut to field dimensio This entails a slight delay in erection but is safe and eminently satisfacto All steam piping, and most water and oil piping, should be carefully **clean of internal scale** (by brushing or hammering), as this may dislodge dur operation and cause trouble in the cylinders of engines or other apparat Steam and water piping should be tested at the working pressure before be put in service.

391. Hangers. Careful provision for hangers at suitable points must made in order to support the pipe properly. The interval between hang should not exceed 12 ft. except for small pipe, which may be supported centers as much as 18 ft. apart.

392. Costs. Valves cost, in cast-iron body, approximately \$0.20 to \$0 per lb; straight cast-iron pipe, 12-ft. lengths, \$34.00 to \$50.00 per t straight pipe, shorter than 12-ft. lengths, \$52.00 to \$60.00 per ton; stand fittings, \$60.00 to \$75.00; special fittings, \$73.00 to \$113.00 per t Wrought-iron and steel pipe, 1-in. to 6-in. sizes, costs from 3.4 to cents per lb.; 7-in. and 8-in. 4.3 to 5 cents; 10-in. to 12-in., 5 to 6 ce per lb. All the recent evidence seems to show that wrought-iron p is no better than steel for practically all purposes; and as the steel pip lower in price and more readily available, it is satisfactory to use it (1914)

PLANT ENSEMBLE

393. The best combination of plant equipment is seldom if ever in which each piece of apparatus is chosen by reason of its best water rate,

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highest efficiency. The characteristic under variable load and the heat relation to the rest of the plant are most important.

394. The question of first cost versus economy is discussed under power-plant economics (Par. **884** to **931**). The following paragraphs cover the best capacity and grouping of units for the best overall economy, with given efficiencies in the individual apparatus.

395. The heat analysis in B.t.u. is valuable for the purpose of proving the expected economies of any given combination of apparatus. Starting with the coal supplied, the boiler-room distribution of all the heat contents is followed through, including the B.t.u. delivered to steam, flues, unburned combustible, radiation, leakage, stoker, fan, and boiler feed-pump drives, other auxiliaries and miscellaneous steam such as boiler blow-down, free drip, dusting tubes, etc. In the engine room, the B.t.u. supplied in the steam is separated into pipe and engine radiation, exhaust drips, condenser auxiliaries, oil pumps, exciters, friction, electrical losses and energy delivered to bus bars. Heat returned by feed-water heaters and economizers is credited.

396. The average conditions in large stations (100,000 kw. and more) with steam driven auxiliaries, will give the heat distribution stated below. For a 12,000 kw. station, the useful heat in the coal appearing in net output, is approximately 12.5 per cent., with a coal factor of about 2.10 lbs. The coal factor of the station using 30,000 kw. units would be about 1.40 lbs.

	Per cent.	Per cent.
Coal		100.0
Loss in ashes*	2.5	
Stack*	16.0	
Incomplete combustion*	4.0	
Radiation and leakage, boiler	6.0	
Returned by feed-water heater		11.5
Returned by economizer		4.4
Pipe radiation and leakage	2.5	
Condenser auxiliaries	7.5	
Boiler-room auxiliaries	5.1	
Heating	0.2	
Electrical losses, gen. etc.	0.8	
House service	0.2	
Rejected to condenser	53.7	
Net output, switchboard	17.4	
	115.9	115.9

397. In choosing the number and capacity of prime movers, the Willans line of total steam consumption with load is plotted. The arrangement which gives the least area under the curve is the most economical. Fig. 43 shows this curve for 42-in. × 86-in. × 60-in. double compound Corliss engines, 7,500 kw. maximum continuous rating on 190 lb. dry steam, 28 in. vacuum. If the auxiliaries were not considered, the Willans line for engines alone would show the proper points for cutting engines in and out. It is found however, that the most economical method is to carry up the load on n units until the Willans line for n units intersects the Willans line for $n+1$ units; and *vice versa*. The maximum capacity of individual machines may limit the cutting-in point somewhat when only one or two engines are running, but as the number in service increases, the loads on each engine before and after cutting in another unit become nearer alike.

398. Effect of auxiliaries on Willans line. The condensers and other auxiliaries using steam necessitate the addition of their demand to the main-unit demand, and the resulting Willans lines will give the steam demand of the engine room for any load. This supposes the units to be all alike and equally loaded when on the line; however, for units of unequal capacities, various loadings should be tried and plotted in order to determine the most economical operating conditions (Fig. 43).

* Average boiler efficiency, including banking, 71.5 per cent.

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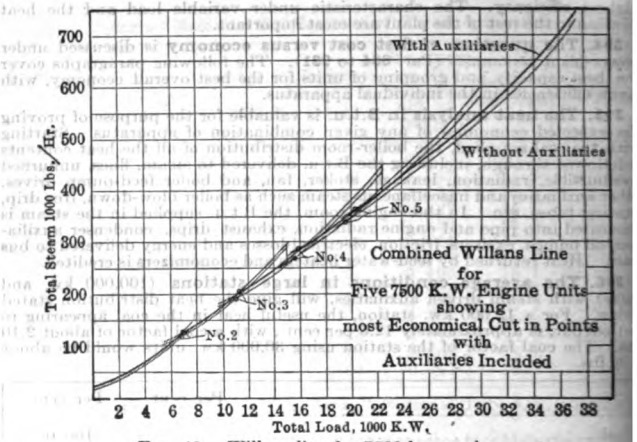


FIG. 43.—Willans line for 7500-kw. engines.

399. The boiler generation curve is determined by the efficiency of t boiler and stoker and by the steam required for forced draft, stoker driv boiler feed pumps, etc. The economical cutting in and out points can developed in the same manner as for the engine room, noting always that it the overall efficiency which is important, not that of the boiler alone.

400. Feed-water heaters recover from 5 to 12 per cent. of the heat of t steam, the source being chiefly the exhaust from auxiliaries operated no condensing. The feed-water heater always pays for itself.

401. Economizers recover from 3 to 10 per cent. of the total heat; b the recent increase of boiler efficiency (reducing the stack temperatures the reversion to all-steam auxiliaries, and the need for more draft at high capacities, is rapidly limiting the field of the economizer; it does not alwa economize. On the other hand, high rate of driving the boiler normal encourages the use of the economizer.

402. Possible reductions in the heat losses. The heat losses are give in Par. **396.** It is clear that: (a) the ash loss cannot be much reduce (b) the stack loss is probably susceptible of considerable improvemen especially by way of improving combustion, which affects stack temperatu indirectly; (c) the incomplete combustion would be decreased with (b (d) the condenser loss is the only other very considerable item, and this ca not, by nature of the cycle, be appreciably altered.

403. The steam consumption per kw-hr. of the plant will depend upo the water rate of the main unit, the steam required by auxiliaries and the los factor. The no-load steam losses include: banked boilers; pipe radiation an leakage; boiler blow-down; boiler dusting; operation of condenser auxiliari on emergency units and boiler auxiliaries, and supplying feed water for the losses. If the load factor is low, these bear a larger proportion to the tota In a high-grade plant with a yearly load factor of 30 to 40 per cent., the statio water rate is 25 to 35 per cent. higher than the best water rate of the mai unit. For ordinary stations of moderate size on less than 25 to 40 per cen load factor, the station water rate is 80 to 100 per cent. higher than that the main unit alone. The steam required for condenser auxiliaries is fro 2 to 3½ per cent. of the main-unit consumption, for engine units, up to 2 in. vacuum; for turbine plants, 4.5 to 10 per cent for 28 in. to 28.5 in. vacuum The boiler feed-pump steam varies from 1 to 1½ per cent. for direct recipro cating pumps, and 0.6 to 1.3 per cent. for high-grade pumping engines, o

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turbine-driven centrifugal types. The steam for forced-draft fans on underfeed stokers varies from 1 to 2 per cent. of main-unit steam; coal-conveying systems require 1.7 to 3 per cent., or the equivalent in electrical energy. The total varies therefore from 8 to 18 per cent.

404. The power taken by the auxiliaries of a 5,000-kw. turbine tested by the Edison Illuminating Co. of Boston was as follows:

Kw. on turbine	2,718.0	3,410.0	4,758.0
Vacuum, in.	28.4	28.7	28.6
Barometer, in.	29.53	29.95	29.96
I.h.p. of boiler-feed pump	13.9	23.7	27.2
I.h.p. of circulating pump	69.1	69.1	69.1
I.h.p. of dry-vacuum pump	24.3	23.2	23.8
I.h.p. of step-bearing pump	6.4	5.8	5.6
Total power for auxiliaries	122.3	131.0	135.7
Per cent. power of auxiliaries	3.4	2.9	2.1
Per cent. water used by auxiliaries	8.4	7.4	5.7
Electric h.p. of wet-vacuum pump	8.6	9.2	9.8

405. Number of main units. In modern central-station practice, the reciprocating engine is practically defunct. For 24-hr. service, not less than three turbine units should be employed and preferably six to eight for large stations. The units should always be of similar size. The analysis given in Par. **397** to **399** will prove that there is very seldom any economy in selecting odd-size units for a plant, and there is always increased risk of shutdown and increased cost, due to lack of interchangeability of units and spare parts.

406. Steam versus electric drive for auxiliaries. The heat analysis shows that the steam auxiliary is generally more economical than the motor-driven type, when the amount of steam required for auxiliaries does not exceed the demand for heat in the feed water. Turbine-driven auxiliaries are practically universal except for the dry-vacuum pumps, which are often reciprocating, and small oil pumps, which are more satisfactory if duplex direct acting. Turbine-driven blast fans are becoming very widely used. Turbine-driven centrifugal boiler feed pumps are very satisfactory in units larger than 300 gal. per min.; in smaller units, the impeller passages are small and likely to give trouble from scaling and clogging.

407. General plant layout. The most generally satisfactory scheme is to lay out the plant on the **unit system**, with a complete set of boilers and auxiliaries for each turbine. The advantages become more and more marked, the larger the plant.

408. Plant location. The plant should be located at the edge of a sufficient body of water to supply abundant condensing water; where this cannot be done, wells may possibly supply the required amount, or, failing this, cooling towers will be necessary. The next most important consideration is coal supply; location on a river or at tide-water may automatically take care of coal supply by barge, but otherwise a rail connection will be needed. The third item is suitable ground for the foundations of the building and machinery. Choice of site where rock bottom is available near the surface is most desirable, but hardpan is practically as satisfactory. On marsh land near rivers or tide-water, piling or fill will be necessary. Too great pains to provide solid and permanent foundations cannot be taken.

409. Load factor plays a large part in selection of a plant; for low load factors, the fixed charges are high, and the operating charges relatively small. It is therefore necessary to cut down the first cost, which is done by omitting refinements for efficiency and allowing the thermal economy to go down. For high load factor, the fixed charges are less important and operating charges become the controlling factor; therefore profitable investment in devices for high thermal economy may be made. For low load factors, machines with high overload capacities are desirable, at the sacrifice of economy. It will be desirable to overstoker the boilers a little, to this end, as well as to build the turbines for high overloads.

410. Reserve capacity of one main unit at peak load should be maintained in plants of any number of units up to eight; above this, two reserve units. This applies to plants with duplicate equipment. For plants with

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dissimilar units, the reserve should be equal to the largest unit in the plant, either as one large unit, or the equivalent load capacity in smaller units.

411. Unit costs of equipment may be taken as given in Par. **57, 88,** etc. But on a basis of plant output, the relations will be different. Lyford and Stovel give the following central station costs, high and low, for steam turbo-electric generating stations of 2,000 to 20,000 kw. capacity, based on maximum continuous capacity of generators as 50 deg. Cent. temp. rise.

Prices are exceedingly variable at the present time, but they may reasonably be taken at twice the figures in 1913 to 1915, for all items. Some individual apparatus, such as boilers, is more than twice as costly, other apparatus less. The net result in May, 1920, is that the total cost is almost exactly double that of 1913.

Costs in 1913	Dollars per kw.	
	High	Low
Preparing Site: Clearing structures from site, construction roads, tracks, etc.	$0.25	.....
Yard Work: Flumes for condensing water, siding, grading, fencing, sidewalks, etc.	2.50	$1.00
Foundations: Foundations for building, stacks and machinery, excavation, piling, waterproofing, etc.	6.00 6.00	1.00 1.00
Building: Frame, walls, floors, roofs, windows, doors, coal bunker, etc., exclusive of foundations, heating, plumbing and lighting.	12.00	4.00
Boiler-room Equipments: Boilers, stokers, flues, stacks, feed pumps, feed-water heater, economizers, mechanical draft, piping and covering, except condenser water piping.	24.00	12.00
Turbine Room Equipment: Steam turbines and generators, condensers, condenser auxiliaries, condenser water piping, oiling system, etc.	22.00	12.00
Electrical Switching Equipment: Exciters, masonry switch structure, switchboards, switches, instruments, etc., all wiring except for lighting.	5.00	2.00
Service Equipment: Cranes, lighting, heating, plumbing, fire protection, compressed air, furniture, permanent tools, coal- and ash-handling machinery, etc.	5.00	2.50
Starting Up: Labor, fuel and supplies for getting plant ready to carry useful load.	1.00	0.50
General Charges: Engineering, purchasing, supervision, clerical work, construction plant and supplies, watchmen, cleaning up, etc.	6.00	3.00
Total cost of plant, except land and interest during Construction.	$83.75	$38.00

412. Reliability is increased by uniform equipment, and by proper reserves. The turbine plant is superior to the engine plant in this respect, with the same number and capacity of units. It is not good practice to operate a unit regularly at overloads, although the machine may always be overloaded for short periods before cutting in or after cutting out a unit. The analysis given in Par. **397** to **399** will show this to be thermally economical.

413. Labor requirements. With the use of very large size turbines and boilers, the labor required has been enormously reduced. With units up to, say, 4000 kw., operating labor in the engine room will run about one man per 1000 to 1500 kw. capacity; boiler room operation, one man per 1,500 kw.; maintenance labor, one man per 2,000 kw. capacity. For 30,000 kw. units or larger, operating labor in the engine room, 6,000 to 7,500 kw. per man; boiler room labor 4,000–5,000 kw. per man; maintenance, 10,000 to 15,000 kw. per man.

Net total for the smaller plants, one man per 500 to 750 kw.; for the large plants, 2,200 to 3,000 kw. per man.

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414. Operating and maintenance costs, for 1915, taken from the port of the Committee on Power Generation, A.E.R.A., 1916, are as follows, a yearly basis.

Net output, million kw.-hr.	130.08	111.08	172.90	91.40
One hr. peak	42,000	33,240	46,100	23,900
Load factor, 1 hr. peak	0.35	0.38	0.428	0.437
Capacity, 2 hr. peak	45,000	37,000	65,700	44,700
Plant load factor	0.33	0.34	0.30	0.234
Lbs. coal per kw.-hr.	1.75	1.97	2.48	2.78
B.t.u. coal as rec'd	14,450	14,250	13,400	13,000
Costs per kw.-hr. mills:				
16. Buildings	0.0130	0.0096	0.05	0.0039
17. Maintenance	0.1237	0.2593	0.65	0.2167
12. Labor, op.	0.2780	0.2594	1.02	0.4469
13. Fuel	2.6710	3.0030	3.71	2.0750
14. Water	0.0243	.....	0.03	0.00001
15. Lubricants	0.0055	0.0220	0.06	0.0226
16. Miscellaneous supplies	0.0425	0.0279	0.24	0.0980
Total	3.1580	3.5812	5.78	2.8632
Per cent. of total:				
16. Buildings	0.41	0.26	1.00	0.13
17. Maintenance	3.93	7.24	11.30	7.57
12. Labor	8.79	7.24	17.60	15.62
13. Fuel	84.57	83.86	64.30	72.47
14. Water	0.78	*	0.62	.....
15. Lubricants	0.18	0.62	1.10	0.79
16. Miscellaneous	1.34	0.78	4.07	3.42
Cost of coal, per million B.t.u.	0.1045	0.1071	0.1116	0.0574
B.t.u. per net kw.-hr.	25,300	28,100	33,232	36,200

TESTING

415. Boiler-testing requires the following essential data: (a) Weight water fed per hr.; (b) weight of coal fed per hr.; (c) quality of steam; pressure and superheat; (e) feed-water temperature; (f) proximate alysis of coal including moisture and B.t.u. per lb. Additional desirable ta includes: (g) Flue temperature, including furnace and pass tempera- res; (h) flue gas analysis, and analyses of gas at various points in boiler; weight of refuse; (k) proximate analysis of refuse, moisture and B.t.u. r lb.; (l) siftings, if stoker fired; (m) soot and dust passing through boiler; steam flow by meters. Boiler testing is always interwoven with stoker ring; the fire and the heating surface are tested together. The **duration** test should never be less than 24 hr., for the most accurate results.

416. Summary of overall results.

TOTAL QUANTITIES

1.	Date of trial	
2.	Duration of trial	hr.
3.	Weight of coal as fired	lb.
4.	Percentage of moisture in coal	per cent.
5.	Total weight of dry coal consumed	lb.
6.	Total ash and refuse	lb.
7.	Percentage of ash and refuse in dry coal	per cent.
8.	Total weight of water fed to the boiler	lb.
9.	Water actually evaporated, corrected for moisture or superheat in steam.	lb.
10.	Equivalent water evaporated into dry steam from and at 212°.	lb.

For further details, see the standard code of the A. S. M. E.

417. Especial care should be taken to isolate the boiler tested so at leakage can be eliminated or measured. No single valve may be con- ered absolutely tight. Where lines cannot be completely disconnected, ere should be two closed valves with a half-inch open bleeder between them indicate leakage. Variations of water level must be corrected for.

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418. For weighing feed water, tanks on platform scales are best: but lacking these, a calibrated recording Venturi meter is satisfactory and accurate within 1 per cent. on reasonably steady flow.

419. For full details as to methods of firing, calorimetry, etc., see standard rules of the A. S. M. E.

420. Heat Balance, or Distribution of the Heating Value of the Combustible

The heat value of 1 lb. of combustible	B.t.u.	
	B.t.u.	Per cent.
1. Heat absorbed by the boiler = evaporation from and at 212° per lb. of combustible × 970.4.		
2. Loss due to moisture in coal = per cent. of moisture referred to combustible ÷ 100 × [(212 − t) + 970.4 + 0.6 (T − 212)] (t = temperature of air in the boiler-room, T = that of the flue gases).		
3. Loss due to moisture formed by the burning of hydrogen = per cent. of hydrogen to combustible ÷ 100 × 9 × [(212 − t) + 970.4 + 0.6 (T − 212)].		
4.* Loss due to heat carried away in the dry chimney gases = weight of gas per pound of combustible × 0.24 × (T − t)		
5.† Loss due to incomplete combustion of carbon = $\frac{CO}{CO_2+CO} \times \frac{\text{per cent. C in combustible}}{100} \times 10{,}150$.		
6. Loss due to unconsumed hydrogen and hydro-carbons, to heating the moisture in the air, to radiation, and unaccounted for. (Some of these losses may be separately itemized if data are obtained from which they may be calculated)		
Totals		100

421. Quality of steam. The percentage of **moisture** in the steam should be determined by the use of either a throttling or a separating steam calorimeter. The sampling nozzle should be placed in the vertical steam pipe rising from the boiler. It should be made of 0.5-in. pipe, and should be extended across the diameter of the steam pipe to within half an inch of the opposite side, being closed at the end and perforated with not less than twenty 0.125-in. holes equally distributed along and around its cylindrical surface, but none of these holes should be nearer than 0.5 in. to the inner side of the steam pipe. The calorimeter and the pipe leading to it should be well covered with felting.

422. Superheating should be determined by means of a thermometer placed in a mercury-well inserted in the steam pipe. The degree of super-

* The weight of gas per lb. of carbon burned may be calculated from the gas analyses, as follows:

† CO_2 and CO are respectively the percentages by volume of carbonic acid and carbonic oxide in the flue gases. The quantity 10,150 = number of heat units generated by burning to carbonic acid 1 lb. of carbon contained in carbonic oxide.

$$\text{Dry gas per lb. carbon} = \frac{11CO_2+80+7(CO+N)}{3(CO_2+CO)}, \qquad (68)$$

in which CO_2, CO, O and N are the percentages by volume of the several gases. As the sampling and analyses of the gases in the present state of the art are liable to considerable errors, the result of this calculation is usually only an approximate one. The heat balance itself is also only approximate for this reason, as well as for the fact that it is not possible to determine accurately the percentage of unburned hydrogen or hydrocarbons in the flue gases.

The weight of dry gas per lb. of combustible is found by multiplying the dry gas per lb. of combustible by the percentage of carbon in the combustible, and dividing by 100.

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ting should be taken as the difference between the reading of the ther-
meter for superheated steam and the reading of the same thermometer
saturated steam at the same pressure, as determined by a special ex-
ment, and not by reference to steam tables.

13. Sampling the coal and determining its moisture. As each
ow-load or fresh portion of coal is taken from the coal-pile a representa-
shove ful is selected from it and placed in a barrel or box in a cool place
kept until the end of the trial. The samples are then mixed and broken
pieces not exceeding 1 in. in diameter, and reduced by the process of
ated quatering and crushing until a fine sample weighing about 5 lb.
btained and the size of the larger pieces is such that they will pass through
eve with 0.25-in. meshes. From this sample two 1-qt., air-tight
preserving jars, or other air-tight vessels which will prevent the escape
noisture from the sample, are to be promptly filled, and these samples
to be kept for subsequent determinations of moisture and of heating
e and for chemical analyses. For further details, see the standard code
he A. S. M. E.

14. Calorific tests and analysis of coal. The quality of the coal
uld be determined either by heat test or by analysis, or by both. The
onal method of determiming the total heat of combustion is to burn the
ple of coal in an atmosphere of oxygen gas, the coal to be sampled as
cted in Article XV of the code. The **chemical analysis** of the coal
uld be made only by an expert chemist. The total heat of combustion
puted from the results of the ultimate analysis may be obtained by the
of Dulong's formula (with constants modified by recent determinations),

$$14{,}600C + 62{,}000\left(H - \frac{O}{8}\right) + 4{,}000S, \qquad (68)$$

hich C, H, O, and S refer to the proportions of carbon, hydrogen, oxygen
sulphur, respectively, as determined by the ultimate analysis. It is
irable that a **proximate analysis** should be made, thereby determining
relative proportions of volatile matter and fixed carbon. These pro-
ions furnish an indication of the leading characteristics of the fuel, and
e to fix the class to which it belongs. As an additional indication of the
racteristics of the fuel the specific gravity should be determined.

15. Treatment of ashes and refuse. The ashes and refuse are to be
hed in a dry state. If it is found desirable to show the principal char-
ristics of the ash, a sample should be subjected to a proximate analysis
the actual amount of incombustible material determined. For elaborate
s a complete analysis of the ash and refuse should be made.

16. A throttling or a Thomas electric calorimeter should be used
re possible, in preference to separating or other types. **Thermometers**
more satisfactory as indicators of saturated steam pressure than spring
es.

17. Engine testing requires essentially: (a) Weight of steam used;
kw. output of generator, or brake h.p.; (c) i.h.p., from indicator cards;
rev. per min.; (e) steam pressure, receiver pressure and back pressure
vacuum; (f) quality of steam. Desirable additional data include: (g)
iver and exhaust temperatures; (h) weight of condensation from receiver
lsewhere; (j) reheater steam, if used.

18. The steam consumption is best obtained by weighing the discharge
n a surface condenser; but if jet condensers are used or the engine is non-
densing, the feed water must be measured as it enters the boilers, the boiler
kage determined, and the boilers isolated from all other steam piping and
aratus. If the condensate is weighed, the condenser leakage must be
rtained. The test should continue not less than 1 to 3 hr., with surface
densers and 8 hr. when using the feed-water method.

19. Turbine testing involves the following essential data: (a) Steam
ght per hr.; (b) initial and exhaust pressures; (c) superheat, or wetness
steam; (d) rev. per min.; (e) b.h.p. or kw. output of generators;
steam chest pressure. There is a general similarity to engine testing,
only real difference lying in the absence of indicator cards. In measuring
condensate, provision must be made for measuring also the gland-water,
steam for sealing purposes, which is not strictly chargeable to the turbine,
e all the water, or all the heat is recovered.

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430. For full data on turbine testing see the standard rules of th A. S. M. E.

431. Condenser testing. The condenser is the chief auxiliary requirin test: generally it is convenient to combine the condenser test with the engi or turbine test on the attached prime mover. The essential readings ar (a) vacuum at exhaust entry referred to standard barometer; (b) condensat weight per hr.; (c) circulating water temperatures at inlet and discharg (d) hot well temperature. Additional desirable data include: (e) vacuu at hot well; (f) vacuum at dry vacuum pump; (g) temperatures, top and bo tom of condenser; (h) temperature of dry air at pump; (j) Pitot or Ventu meter readings on circulating water; (k) temperature of circulating wat at beginning and end of each pass; (l) volume of dry air removed per mi A separate test for leakage should be made before the operating test, and tes for salt may be made on the condensate during the operation, if salt water employed as cooling water.

432. Tests of boiler feed pumps and circulating water or hot-we pumps, of the centrifugal type, require the following readings, for turbin driven units: (a) weight of steam used per hr.; (b) steam and exhau pressures; (c) quality of steam, or superheat; (d) suction and discharge head (e) weight of water pumped—by scales, tank or Pitot or Venturi tube rea ings, which are close enough for this work (weirs may be used for lar pumps); (f) rev. per min.

433. In testing direct-acting steam pumps, indicator cards shou also be taken.

434. For tests of electric driven pumps, readings (a), (b), and (in Par. **432** would be replaced by kilowatt readings on the motor.

435. Tests on turbine-driven fans for forced or induced draft requir (a) Steam used per hr.; (b) steam pressure and back pressure; (c) qualit of steam or superheat; (d) Pitot static and dynamic readings on suitab fan outlet; (e) rev. per min. For motor drive, kilowatt readings will repla (a), (b) and (c).

436 Complete plants have what amounts to a continuous test i their regular records, if properly kept. Coal is bought and paid for b weight and by analysis; and recording wattmeters give the output. Fe yearly figures the plant storage usually is not an important factor, as i amount is small compared to the total consumption; but for monthly figure a survey of the coal stored is necessary. This is usually made by takin readings at predetermined points over the bunkers or storage space and ca culating the volume of coal, allowing generally 50 lb. per cu. ft. for bituminou coal and 54 lb. per cu. ft. for No. 1, No. 2 or No. 3 buckwheat anthracite.

437. The apparatus required for weighing water is preferably mad up of one or more sets of tanks on platform scales; the accuracy may be kep to 0.25 per cent. quite readily. Where less accuracy is required, 0.5 to 1. per cent., measurement by volume in a tank, or by Venturi meter, or V-notc weir, is suitable.

438. For measuring the steam used, the best method is by surfac condensers (which may be made substantially tight), using scale tanks f weighing the condensate.

439. For measuring temperature up to 900 deg. Fahr., mercur thermometers of 12 in. length are most convenient; they should be used i iron or brass wells, with a little mercury in the bottom of the cup, and th remainder filled with oil. For temperatures above 500 deg. Fahr., nitroge filled mercury thermometers must be employed. Care should be taken t ascertain the immersion for which the thermometer is calibrated. Resist ance thermometers are now available, but are in general very much mo expensive; their use is a convenience where there are several inaccessibl readings to be taken, as all the resistance bulbs may be read from one ga vanometer and bridge. For higher temperatures than 900 deg. Fahr., resis ance thermometers or thermocouples should be used. For high furnac temperatures, radiation or optical pyrometers are best. (Sec. 3.)

440. For pressure measurements, the spring gage is convenient bu usually inaccurate; for pressures up to 15 lb., mercury columns are far bette For steam pressure, the thermometer is a valuable and accurate means o

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ng results. If the steam is superheated, a thermometer in a pressure ıber separated from the steam main by a condensing coil, and suitably ıed, will give correct readings of pressure. If gages are used, they ld be carefully checked at the operating pressure, in position if possible, ıst a standard gage tester.

1. **Frequency of observations.** Observations of temperatures, ures and speeds should occur once every 10 or 15 min. Water and coal hings should be made as often as needed by the capacity of the con- rs on the scales. Wattmeter readings and coal and water readings ld be balanced every hour, as a precautionary measure in checking the liness and reliability of the test. Calorimeter readings on boilers and nes at steady load only need be taken at half-hourly or hourly intervals, ey vary but little. Barometer readings taken three times during a test ufficient. For short tests, such as occur in motor-driven pumps and fans Pitot tube or Venturi tube readings, instantaneous values taken once nute for 10 min. gives good enough results as a rule. Pitot readings ir should be taken at numerous points in the pipe (see Treat, *Trans.* M. E., 1912, and Rowse, *Trans.* A. S. M. E., 1913.

1. **Duration of tests.** Engine or turbine tests by the feed-water od should not be less than 8 hr., as the error introduced by variations of in the boilers is too great on shorter tests; when weighing the condensate, 3 hr. will be sufficient, depending on reservoir capacity in the system. re flow meters can be employed with sufficient accuracy, instantaneous of a few minutes duration may be run. The time taken for a boiler start to stop, should never be less than 10 hr., 12 are better and 18 to 24 ive much more consistent results. This length of time is needed on unt of the variable error introduced by the unknown amount of coal ne fire at start and finish.

3. **Precision of tests.** Boiler tests of 10 hr. duration are seldom closer 3 per cent. either side of the average; 12-hr. tests, 2.5 per cent.; 24 hr. cent. Engine tests of 8 hr. duration, will have a probable error of 2 ent., either way; turbine tests of 3 hr., 2 per cent. It is therefore need- o compute results closer than $\frac{1}{10}$ of 1 per cent.

GAS POWER PLANTS

BY REGINALD J. S. PIGOTT

PRODUCERS

1. **Destructive distillation** can occur only with fuels containing ile matter; therefore anthracite and coke producers cannot be said to ate by destructive distillation. **Gas** may be produced from **hard coal** llows: with air only, $2C+O_2=2CO$; with steam only, $H_2O+C=CO$; with both steam and air, $3C+O_2+H_2O=3CO+H_2$. The first ss is not often used; the second is used to make **water gas**, but since s not produce heat, it is used intermittently with the process $C+O_2=$ or simple combustion of the fuel in the producer to generate the necessary This is called "blasting up." The third process is the one used in ng **producer gas** from anthracite or coke.

1. **With bituminous coals,** the volatile matter is given off as tar and ocarbon gases of the methane series, chiefly. These are again broken r the heat in the producer to methane, carbon monoxide and hydrogen. ldition, the formation of CO and H from the coke remaining, goes on antially as in the anthracite producer. In the down-draft types of ucers, the tar passes through the fuel bed and is broken down to com- ble gases and lampblack, some of which are burned in the passage.

6. **Suction producers** obtain a flow of air, steam and gas by means of ght difference of pressure due to the pump action of the four-cycle ngine on the charging stroke, or by an exhauster.

7. **Pressure producers** obtain a flow of gas, etc., by means of a ure fan or blower for the air, or a boiler for the steam. A pressure ucer is independent of the engine, and does not affect the capacity of atter.

8. **Up-draft producers** are arranged with the steam and air admitted e bottom and gas removed from the top; tar passes off with the gas and ; be removed by scrubbers and purifiers.

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FIG. 44.—Loomis-Pettibone down-draft producer.

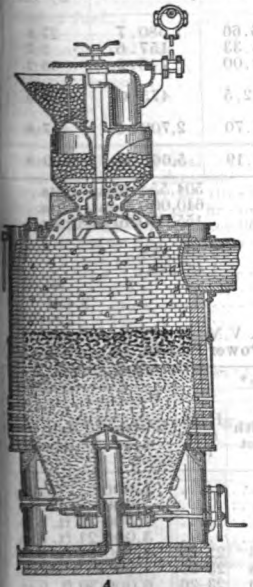
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449. Gasification of Anthracite Coal (R. D. Wood Co.)

Process	Products		
	Lb.	Cu. ft.	Anal. by Vol.
80 lb. C burned to CO	186.66	2,529.24	33.4
5 lb. C burned to CO_2	18.33	157.64	2.0
5 lb. vol. HC (distilled)	5.00	116.60	1.6
120 lb. Oxygen are required, of which			
30 lb. from H_2O liberate H	3.75	712.50	9.4
90 lb. from air as associated with N.	301.05	4,064.17	53.6
	514.79	7,580.15	100.0

Energy in the above gas obtained from 100 lb. anthracite: 85 per cent. F.C.; 5 per cent. V.M.; 10 per cent. ash.

186.66 lb. CO	807,304 B.t.u.
5.00 lb. CH_4	117,500 B.t.u.
3.75 lb. H	235,500 B.t.u.
	1,157,304 B.t.u.
Total energy in gas per lb	2,248 B.t.u.
Total energy in gas per cu. ft	152.7 B.t.u.
Efficiency of conversion	86 per cent.



A

FIG. 45.—Taylor or Mond up-draft producer.

450. Down-draft producers are arranged with air and steam supply at the top, and gas removal under the firebrick grate at the bottom. The **double-zone producer** has down draft in the upper zone and up draft in the lower.

451. Suction producers have the advantage of not allowing gas to escape into the operating room from the producer, as the carbon monoxide is intensely poisonous; and poke openings, etc., can be conveniently operated. For small sizes, no exhaust fan is used, the necessary draft being provided by the engine suction. Most of the down-draft producers are suction types with exhaust fans. In this class belong the Loomis-Pettibone, De Lavergne, Körting, United Gas Machinery Co., Westinghouse double-zone, Otto, and Mond (small size).

452. Pressure producers require forced draft supplied by a fan or a steam jet blower, the steam thus admitted being used in the gasification. The tar formed is carried over with the gas and requires more extensive cleaning, but access to the grates is better than with the down-draft and suction types and mechanical stoking or poking may be employed either by mechanical water-cooled pokers, or by rotating the ash table and in some cases the producer shell. Examples of this type are the Mond large size, Taylor, and Chapman.

453. The capacity of a producer is based on 0.065 to 0.075 sq. ft. of cross-sectional area per brake h.p. of engine and about 0.105 to 0.118 cu. ft. of volume per h.p. (Snell).

454. The continuous rate of gasification with high-grade coal will not exceed 23 lb. of coal per hr. per sq. ft. of fuel bed; 12 lb. is a good average figure.

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455. Gasification of Bit. Coal, Low Volatile

Process	Products		
	Lb.	Cu. Ft.	Per cent. by Vol.
65 lb. C burned to CO	151.6	2,054	30.8
5 lb. C burned to CO_2	18.3	157	2.3
20 lb. vol. HC (distilled)	20.0	466	7.0
25 lb. O, from water liberate H	3.1	588	9.0
75 lb. atmos. O mixed with N	251.2	3,391	50.9
	444.2	6,656	100.0

Calorific energy of the gas ..... 1,247,870 heat-units.
Calorific energy of the gas per lb. ..... 2,809 heat-units.
Calorific energy of the gas per cu. ft. ..... 187.4 heat-units.
Calorific energy of the coal ..... 1,415,000 heat-units.
Efficiency of the conversion ..... 88 per cent.
Prox. Anal.: 70 per cent. F.C.; 20 per cent.; 10 per cent. ash.

456. Gasification of Bituminous Coal, High Volatile

Process	Products		
	Lb.	Cu. Ft.	Per cent. by Vol.
50 lb. C burned to CO	116.66	1,580.7	27.8
5 lb. C burned to CO_2	18.33	157.6	2.7
32 lb. vol. HC (distilled)	32.00	746.2	13.2
80 lb. O are required, of which 20 lb. derived from H_2O, liberate H	2.5	475.0	8.3
60 lb. O, derived from air, are associated with N	200.70	2,709.4	47.8
	370.19	5,668.9	99.8

Energy in 116.66 lb. CO ..... 504,554 heat-units.
Energy in 32.00 lb. Vol. HC ..... 640,000 heat-units.
Energy in 2.50 lb. H ..... 155,000 heat-units.
1,299,554
Energy in coal 1,437,500
Per cent. of energy delivered in gas 90.0
Heat-units in 1 lb. of gas 3,484
Heat-units in 1 cu. ft. of gas 229.2
Prox. Anal.: 55 per cent. F.C.; 32 per cent. V.M; 12 per cent. ash.

457. Space required for Single-unit Gas Power Plants (Approximat

H.p.	Suction			Pressure*			Gas holders	
	Length feet	Width feet	Head room feet	Length feet	Width feet	Head room feet	Cubic feet	Tank diameter
25–50	13–14	9–11	13–15	.....	.....	.....	1,000	15 ft.
50–75	14–15	10–12	14–17	.....	.....	.....	2,000	17 ft.
75–100	15–19	11–14	15–20	.....	.....	.....	2,500	19 ft. 6 in.
150	20–21	13–15	19–20	.....	.....	.....	3,000	21 ft. 6 in.
200	22–23	15–16	22–23	32	16	22–25	4,000	21 ft. 6 in.
300	25–26	16–17	23–25	34	18	23–25	5,000	24 ft.
400	.....	.....	.....	36	20	23–26	6,000	30 ft. 6 in.
500	.....	.....	.....	2 units 39	22	23–26	10,000	35 ft.
1,000	.....	.....	.....	3 units 39	47	23–26	15,000	43 ft.

Area depends of course on number and size of units for the total pow given.

* Pressure plants exclusive of holder.

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458. The efficiency of large producers will vary from 70 per cent. to 80 per cent. if the gases are used cold, and 80 to 90 per cent., if used hot (for furnace work). The losses include: (a) Sensible heat in gases; (b) producer radiation and conduction; (c) combustible in ash. The carbon in the ash of a properly operated large producer will be from 4 per cent. to 12 per cent. for about 0.5 to 1.5 per cent. total heat loss, with a coal having 10 per cent. to 12 per cent. ash. For small producers, suction type, the carbon in the ash may be as much as 60 per cent. of the total refuse, and the efficiency of the whole producer from 44 to 75 per cent. The sensible heat in the gases varies from 4 to 19 per cent., usually about 15 per cent. average.

459. Heat balance. The following data on the test of a Loomis-Pettibone producer were taken from the N. E. L. A. report on gas engines, 1908.

Total heat in fuel	100	per cent.
Total heat in gas at 60 deg. fahr	84.7	per cent.
Total heat removed by scrubber	8.16	per cent.
Total heat removed by water cooled valves	1.56	per cent.
Total heat lost by radiation, etc.	5.58	per cent.
	100.00	

460. Tests on a 60-h.p. Otto Suction Producer

No. of test	21	16	17	27	25
Duration, hr	12	12	12	12	12
Kind of fuel	Lehigh chestnut			Scranton pea	
Proximate analysis					
Fixed carbon	80.11	73.59	77.39	75.54	78.45
Volatile matter	4.27	8.47	6.70	6.34	5.99
Moisture	1.95	3.98	1.11	2.90	2.75
Ash	13.67	13.96	14.81	15.22	12.81
Sulphur	1.08	1.41	0.63	1.71	1.10
B.t.u. per lb., dry coal	12,750	12,780	12,680	12,540	13,040
B.t.u. per lb., combustible	15,570	15,550	15,700	15,700	15,700
Dry coal fired per hr. (lb.)	12.78	49.40	82.90	24.75	64.70
Water to producer per hr. (lb.)	22.2	30.40	42.05	16.30	28.50
Dry air per hr. to producer (lb.)	58.8	202.5	386.0	87.5	259.2
Calorific value gas, b.t.u./cu. ft.	104.8	111.8	103.4	120.0	137.3
Wt. dry gas per hr. (lb.)	69.0	248.6	456.0	105.0	326.0
Gas analysis, CO_2 (per cent.)	9.17	6.46	6.94	5.90	4.20
..... CO	16.06	27.77	21.33	21.70	27.01
..... O_2	0.53	0.49	0.37	0.40	0.23
..... H_2	9.55	9.53	7.06	10.70	10.40
..... CH_4	2.10	1.74	1.90	1.60	1.77
..... N_2	62.65	59.01	62.50	59.70	56.40
Cold gas efficiency (per cent.)	54.3	65.8	64.6	56.4	76.2

461. Tests of Westinghouse Double-zone Producer

Fuel	Pocahontas	Texas lignite
Duration	96 hrs.	46.5 hrs.
Total coal fired	14,452 lb.	12,693 lb.
Heat value per lb	13,983 B.t.u.	8,007 B.t.u.
Heat value per cu. ft. (total)	126.9 B.t.u.	128.3 B.t.u.
Heat value per cu. ft. (effective)	117.8 B.t.u.	117.1 B.t.u.
Efficiency (total)	80%	77.3%
Efficiency (effective)	74.5%	70.5%

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Gas Analysis

Carbon dioxide	(CO_2)	7.9%	12.4%
Oxygen	(O)	0.5	0.9
Carbon monoxide	(CO)	18.1	13.3
Marsh gas	(CH_4)	2.6	3.6
Hydrogen	(H)	12.6	14.7
Nitrogen	(N)	58.3	55.1

In the above table all values are computed on the assumption that the gas is at a temperature of 62 deg. Fahr., and that the absolute pressure is 30 in. of mercury.

462. Tests of Wood Pressure Producer

(Gas plant test—24 days continuous running)

*COAL	per cent.	GAS: Average	per cent.
Moisture	14.68	Carbon dioxide	CO_2 = 9.2
Volatile combustible	30.98	Oxygen	O_2 = 0.0
Fixed carbon	42.93	Ethylene	C_2H_4 = 0.4
Ash	11.41	Carbon Monoxide	CO = 20.9
		Hydrogen	H_2 = 15.6
	100.00	Methane	CH_4 = 1.9
Sulphur	1.33	Nitrogen	N_2 = 52.0

Calorific power 12,343 B.t.u. per lb. of dry coal.
Average heat value of gas for 24 days = 156.1 B.t.u. per cu. ft.

On the average of the Government tests generally Prof. Fernald gives the following:

463. Tests by Geological Survey

Load 90—100 Per cent. 30 to 50 hr.	Bituminous		Lignites		Peat	
	As fired	Dry	As fired	Dry	As fired	Dry
B.t.u. per lb. of fuel	12,280	13,150	8,350	11,290	8,127	10,289
Cu. ft. of gas per lb.	60.5	64.7	35.8	45.7	30.3	38.3
B.t.u. per cu. ft. of standard gas.	152.1	.....	158.4	.....	175.2	.....
Total lb. per b. h.p. hr.	1.36	1.26	1.99	1.68	2.57	2.03

464. Quantity of gas per lb. of fuel in up-draft pressure producers is given in Par. **462** (Fernald, Tech. Paper No. 9, Bur. Mines., 1912).

465. The addition of excess steam over that theoretically required, if not too large, has little or no effect on efficiency, but gives more control over clinker formation. The steam required at 30 to 60 lb. gage is 0.33 to 2.5 lb., averaging 0.7 to 1.0 lb., per b.h.p. The highest figures are for by-product recovery plants.

466. Analyses of gas are given in **Par. 128, 459, 460,** and **463.**

467. The operation of gas producers presents three main features: (a) maintenance of uniform resistance of bed, which includes regulation of feed and poking; (b) removal of ash; (c) prevention of clinker. In the case of up-draft producers coal is fed usually by an air-lock device and spreader; poking is done through holes in the top, to fill up holes or channels which may have formed by clinkering and arching, or by localized combustion. Poking must be carefully done to avoid starting the evils it is intended to correct. A moderate rate of driving will tend to keep fires in better condition, as the producer cannot be forced to the same extent as a boiler and give satisfactory results. The down-draft producer can be poked in the same manner as the suction producer.

468. The cost of producers (1920) complete with auxiliaries ranges as follows: Suction producers, up to 300 h.p., total cost = $1600 + 23.0 \times$ (h.p.) (69)

*Prof. R. H. Fernald.

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Pressure producers, up to 300 h.p., total cost = 1800 + 30 × (h.p.) (70)
Pressure producers, above 300 h.p. Total cost = 4,000 + 28 × (h.p.) (71)
Repairs and maintenance vary from $0.35 to $0.55 per h.p. per year. Guarantees on maintenance are usually 2 to 3 per cent. of first cost a year.

SUPERHEATERS AND CONDENSERS

467. The laws of heat transfer for superheaters have been covered in Par. **15** to **29**, and for economizers in Par. **320**, for vaporizers in Par. **2**, **3** and **4**.

470. Superheaters are attached to the vaporizers of some types of producer, to superheat the steam fed to the fuel bed. They are usually of the protected type, heated by the hot gas leaving the producer, and delivering superheated steam for use in the fuel bed. Some additional economy is gained by their use.

471. Wash boxes are water seals and serve the purpose of a check valve to prevent blowing back of gas. They are made of cast iron generally, with a cross-section equal to about 25 times the delivery pipe. The submersion of the entering pipe is about 3 in.

472. Economizers are employed for preheating the air fed to the producer and operate on the sensible heat of the gas leaving the producer.

473. Vaporizers or boilers are attached to nearly all producers, and serve to yield the necessary steam for gasification, abstracting sensible heat from the hot gas. They are usually built much like a vertical fire-tube boiler, or of cast-iron cooling chambers forming the top or side, of the producer.

474. Condensers are employed to remove the tar, and consist usually of chambers with iron baffles upon which the viscous tar impinges and collects; suitable drainage allows the tar to be recovered and removed. The general design is similar to an oil separator. Some are made with helical passages to secure centrifugal action. There are also one or two designs of mechanical tar extractors built like centrifugal fans, to throw out the tar by centrifugal force. They are generally made entirely of cast-iron.

475. Operation. The operation of superheaters requires practically no labor; vaporizers in this respect are the same as boilers; **tar separators** require periodic cleaning and continuous drainage. The tar is inclined to accumulate and thicken with the dust in the gas. The standby period for lignite or bituminous producers is from 6 to 10 hr. a week for cleaning purposes and repairs, on the average. Anthracite producers may be run 60 to 90 days continuously. (Latta, 1910.)

476. The cost of these auxiliaries is included in the cost of the producer, given in Par. **468**, since they are essential to operation.

SCRUBBERS AND PURIFIERS

477. The impurities found in producer gas are dust, tar and ammonia. Dust is blown over from the fuel bed, being usually the ash from the fines in the coal. In some cases, lampblack is also carried over in the down-draft and double-zone types. Tar is the result of partial decomposition and is a combustible material. Ammonia is produced by the union of H dissociated in the producer with N in the air supplied.

478. Two methods of cleaning are generally used: (a) wet scrubbing, with stationary towers and water spray in some form, or mechanical scrubbers more or less like fans with water injection; (b) dry scrubbing, with purifiers or filters made with excelsior or shavings, which require periodic removal and cleaning.

479. Wet scrubbers consist of steel towers filled with coke, wire netting or wood latticing, somewhat after the fashion of a cooling tower. Water is sprayed down from the top, and divides into fine streams or spray, washing out solid impurities and tar, dissolving out ammonia and sulphur gases. The amount required varies from 1.5 gal. to 2.5 gal. per b.h.p. per hr.

480. The mechanical washers are chiefly heavy-built fans with water spray devices, or Theisen washers. The simple fan washer consists of centrifugal fans of heavy construction, usually with cast-iron casing, with a water spray device at the inlet to produce a spray curtain or fog through which the gas passes. The efficiency averages about 12 to 1, gas containing 1.75 to 2.65 gr. per cu. ft. being cleaned to 0.15 to 0.22 gr. per cu. ft. The h.p.

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required per 1,000 cu. ft. per hr. is 0.066. With two fans in series, the cleaning is from 50 to 1, to 200 to 1 and the h.p. required is 0.184 to 0.283 per 1,000 cu. ft. per hr. The water required per fan is 0.0125 to 0.0150 gal. per cu. ft. cleaned per hr.

481. The Theisen washer consists of three elements in one casing: (a) a primary cleaning fan at the suction end; (b) an annular chamber between a drum fitted with helical vanes and a coarse mesh grating surrounding the drum; (c) a discharge fan chamber. Water spray is fed in at the suction chamber and tangentially in the grating. The water consumption is 0.0272 gal. per 1,000 cu. ft. per hr.; the h.p. required is 0.184 per 1,000 cu. ft. per hr. cleaned.

482. The by-products recovered from bituminous coal gasification are ammonium sulphate and tar. The recovery of ammonium sulphate requires the addition of an acid tower, through which dilute sulphuric acid is circulated as in a purifier. The acid removes the ammonia gas as ammonium sulphate. Tar is removed by separators or condensers, and may be used as a fuel in certain oil engines; it usually contains considerable moisture—up to 20 per cent., on account of the water employed in washing the condenser trays.

483. Purifiers or dry scrubbers consist of a steel tank or tower, filled with shavings, excelsior, coke, or Laming composition. Laming composition is a mixture of bog iron ore and shavings. It is used in 6-in. to 8-in. layers, on gratings, and absorbs cyanides and sulphur compounds. The Laming mixture is removed and exposed to the air from time to time, which regenerates the materials for use again. Shavings and other mechanical dry purifying material must be removed and replaced by fresh material as often as they become clogged. Wet scrubbers are automatically cleaned by the water used to precipitate dust. The Smith tar extractor consists of a diaphragm of glass wool, which causes the separation of tar without the use of water except for cooling.

484. Cost of the apparatus is included in the cost of producers, Par. 468.

HOLDERS

485. Gas storage is required to provide reserve capacity for sudden increase of demand, and to absorb excess generation when sudden decrease of load occurs.

486. The holder is of the regular collapsing gasometer type, in no way different from the ordinary illuminating- as tank. In some cases the water seal in the base is used as an additional wash-box for incoming producer gas.

487. The capacity required varies from 40 to 25 cu. ft. up to 100 h.p.; 20 to 15 cu. ft. up to 1,000 h.p. The larger the number of units the less storage usually required, as manipulation is more flexible.

488. The operation of gas holders requires only occasional painting to protect the tank, yearly cleaning of sediment from the water reservoir, and suitable steam-supply to the lift seals to prevent freezing in winter.

489. The cost of gas-holders varies from $1.40 to $0.75 per cu. ft. including foundations (1920).

PROPERTIES OF GAS

490. Calorific Value of elementary gases. (From Gas Engine Design —Lucke.)

Fuel	B.t.u. per lb.		Lb. per cu. ft. at 62 deg. fahr.	B.t.u. per cu. ft.	
	High	Low		High	Low
H.....	61,524.0	51,804.0	.00538	331.0	278.7
CO.....	4,395.6	4,395.6	.07498	329.58	329.58
CH_4.....	24,021.0	21,592.8	.04308	1,037.22	932.38
C_2H_4.....	21,222.0	19,834.2	.07631	1,619.45	1,513.55

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91. Producer gas has a specific gravity, referred to air, of 0.97, average ific heat, 0.25. It varies in composition, not only with the type of pro-er, but from variations in operation of the same producer. The hydrogen tent, being usually high, limits the compression, usually from 100 to 160 per sq. in., with 18 to 5 per cent. of hydrogen, average pressure 135 lb. eful jacketing of valves and pistons for large engines raises the obtainable pression.

92. Natural gas is the richest of the power gases, and is obtainable efly through the soft coal and oil regions. Ohio, Indiana, Illinois, Pennsyl-ia and Virginia are most favored in this way. The allowable compression ies from 75 to 130 lb. The specific gravity referred to air is approxi-tely 0.40 to 0.50; density, 0.043 to 0.049 lb. per cu. ft.

93. Illuminating gases, either coal or water gas, are usually too ex-sive for use in any but the smallest engines, up to say 75 h.p. The allow-e compression is 60 to 100 lb. average 80; specific gravity approximately) to 0.43 for coal gas, 0.57 for water gas.

94. Blast-furnace gas is the leanest of the gases and will stand compres-n from 120 to 190 lb., averaging 155 lb.; this is on account of the dilution h N, and low hydrogen. It is used only in large gas engines at steel mills.

GAS ENGINES

96. Gas-engine cycles. The thermodynamics of the gas engine is plicated by the fact that not only the change of state by expansion and pression occurs in the cylinder, but also the combustion. The order of nts in the usual Otto or **four-stroke cycle** is as follows: aspiration of a rge into the cylinder (suction stroke); compression, approximately adia-ic on the instroke; ignition and explosive combustion at constant volume, ile the piston is on or near the dead centre; and approximately adiabatic pansion on the second outstroke; partial expulsion of the burnt gases at nstant volume when on the outer dead center, further expulsion on the ead instroke, at atmospheric pressure. **The two-stroke cycle** eliminates suction and exhaust strokes, by admitting the incoming charge under a pounds pressure while the piston is on or near the outer centre, after the tial exhaust to atmospheric pressure and constant volume has just taken ce. This incoming charge sweeps before it, by displacement, most of the aining burnt gases.

96. The standard reference diagram put forward by Lucke is useful investigating the performance or design. This diagram is an assumed icator card based on the assumption that the mixture in the cylinder will ave the same as pure air. The general relations are as given below.

97. Compression pressure.

$$p_b = p_a\left(\frac{v_a}{v_b}\right)^{1.41} \quad \text{and} \quad t_b = t_a\left(\frac{v_a}{v_b}\right)^{1.41} \tag{72}$$

ere $p_a = 14.7$ lb. per sq. in., suction pressure; p_b = final compression ssure; v_a = total cylinder volume in cu. ft. = displacement plus clearance; compression volume, or clearance, in cu. ft.; t_a = absolute initial mperature (deg. Fahr. + 461); and t_b = absolute compression temperature.

98. The pressure rise on explosion depends on the amount of heat r cu. ft. of mixture.

$$p_c = p_b\left(\frac{Q}{C_v t_b} + 1\right) \quad \text{and} \quad t_c = t_b + \frac{Q}{C_v} \tag{73}$$

ere p_c = explosion pressure; Q = B.t.u. per lb. of mixture; C_v = specific at at constant volume; t_c = absolute explosion temperature; and the other mbols are as above (Par. 497).

$$p_c - p_b = \frac{2.2\ Q}{\left(\frac{p_a}{p_b}\right)0.71\ v_a} \text{ (in lb. per sq. in.)} \tag{74}$$

99. B.t.u. per cu. ft.

$$\frac{Q}{v_a} = \frac{H}{n + a' + 1} \tag{75}$$

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where H = B.t.u. per cu. ft. of mixture, hot; a' = cu. ft. of air required burn 1 cu. ft. gas; and n = cu. ft. of neutral added. The actual pressu ratio p_c/p_b obtained is from 40 per cent. to 65 per cent. of the air card ratio

500. Expansion is taken according to the law

$$p_d = p_c\left(\frac{v_c}{v_d}\right)^{1.41} \quad (7$$

which is the same as for compression.

501. Efficiency.

$$E = 1 - \frac{t_a}{t_b} = 1 - \left(\frac{p_a}{p_b}\right)^{0.29} \quad (7$$

where E = thermal efficiency of the cycle; other symbols are as abov The thermal efficiency of the ideal cycle is only dependent upon the ra of compression to suction pressure.

502. Four-cycle engines are built in all sizes; the terms single and doul acting have the same application as for steam engines. The majority engines of small and moderate size are single acting. Large engines a generally made double acting, to economise space, as the gas engine is ev more bulky per h.p. than the steam engine.

503. Two-cycle engines are also used in all sizes, but are found to t greatest extent in large units, double acting. For small units they are nev built double acting, as separate pumps are then required to give the pressu for charging at the end of each stroke. In the small single-acting types, t mixture is compressed between the piston and the crank case.

504. Cylinder jackets are essential to practically all gas engines. T enormous heat developed during explosion would soon destroy the cylind and piston if they were not protected by cooling. In most cases this is do by **water jacketing**; in a few small engines, **air cooling** is employe Pistons smaller than 15 in. in diameter are not separately cooled by wa jacketing; but above this size, the area of piston head is too large to properly cooled by conduction to the jacketed cylinder walls, and the ai the crank case; therefore water cooling becomes necessary.

505. The quantity of jacket water should be about 6.5 gal. per b.h. hr. at 50 deg. Fahr., 7.75 gal. per b.h.p.-hr. at 60 deg. Fahr., 9.75 g per b.h.p.-hr. at 70 deg. Fahr., and 12 gal. per b.h.p.-hr. at 80 d Fahr., for large units. Most of this may be recovered and re-used if cool If a cooling tower is used, for recooling the jacket water, about 8 per ce is lost by evaporation. The heat loss to the jacket is from 25 to 50 per cen generally the largest with small engines.

506. Mean effective pressure is computed from the indicator card in same manner as for a steam engine. The m.e.p. of the reference diagra given by

$$\text{M.e.p.} = \frac{5.41Q}{(v_a - v_b)}\left\{1 - \left(\frac{p_a}{p_b}\right)^{0.29}\right\} \quad (5$$

or

$$\text{M.e.p.} = 5.41\left(\frac{H}{a'+1}\right)\left\{1 - \left(\frac{p_a}{p_b}\right)^{0.29}\right\} = C\left(\frac{H}{a'+1}\right) \quad (5$$

where the symbols have the same meaning as in Par. 497 to 500.

For constants to be used with these equations see Par. 507.

507. Constants used in Calculation of M.E.P. (Par. 506)

Compression		Value of factor $C = 5.41 \times 1 - \left(\frac{p_a}{p_b}\right)^{0.29}$	Compression		Value of fac $C = 5.41 \times 1 - \left(\frac{p_a}{p_b}\right)^{0.2}$
Atmospheres	Lb. per sq. in.		Atmospheres	Lb. per sq. in.	
3	44.1	1.474	8	117.6	2.446
4	58.8	1.787	9	132.3	2.554
5	73.5	2.014	10	147.0	2.630
6	88.2	2.187	11	161.7	2.711
7	102.9	2.327	12	176.4	2.775

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508. Observed mean effective pressures obtained by test are given by Lucke:

Fuel	Compression, lb. per sq. in. abs.	M.e.p. actual lb. per sq. in.	Fuel	Compression, lb. per sq. in. abs.	M.e.p. actual lb. per sq. in.
City gas.....	45	45	Producer gas..	103	63
	60	80		108	88
	66	95		125	51
	91	90		141	83
	70	60		170	73
				95	100
Natural gas ...	127	68		95	90
	130	82		90	62
	135	90		115	103
			Blast-furnace gas.....	.....	60
				140	47
				153	81

509. The ignition of gas engines is practically entirely electric. The jump-spark or high-tension spark system is not used for power-station engines. Make-and-break systems are used, because more reliable and effective. The principal troubles are insulation breakdowns, worn and dirty contacts or short-circuiting by jacket leaks.

510. The timing of ignition affects the work done by a given charge and the economy. Ignition should take place so as to give a nearly vertical explosion line. The spark should be advanced, theoretically, as the rate of propagation is decreased by weakening the mixture or the compression, but in practice the spark is usually fixed to give the best results at the average load condition, and is not varied.

511. The speed of gas engines is about the same as for steam engines of the same class. See Par. **170**. In small engines the speed may be 10 to 15 per cent. higher.

512. Indicated horse-power is obtained in the same manner as for steam engines, except that care must be used in planimetering the card to go around the negative work areas in the right direction. For throttle governed engines, the number N in formula 34a, is the same as rev. per min. for 2-cycle engines and rev. per min./2 for 4-cycle engines; with engines governed by the hit-and-miss method, the number of explosions must be counted to get N, as it has no fixed relation to rev. per min.

513. The friction is usually higher in the gas engine than in the steam engine; the mechanical efficiency at full-load is seldom over 85 per cent., even for large engines. Lucke gives.

	Mech. Efficiency	
	4-cycle	2-cycle
Large engines, 500 h.p. and over.....	0.81 to 0.86	0.63 to 0.70
Medium, 25 to 500 h.p.....	0.79 to 0.81	0.64 to 0.66
Small, 4 to 25 h.p.....	0.74 to 0.80	0.63 to 0.70

514. Lubrication is entirely by machine oil, as the cylinder walls are water cooled. Lubrication in general is handled exactly as with the steam engine. About 1 gal. of oil is required per 4,000 b.h.p.-hr.

515. The rated capacity of a gas engine is preferably based on cu. ft. of cylinder displacement. The displacement per h.p. per lb. of mean effective pressure is 229.17 cu. ft. per min. For a given b.h.p. required, the mechanical efficiency is assumed and the i.h.p. found; and with a suitable

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m.e.p. for the fuel employed (Par. 508), the required displacement per h. divided into required i.h.p. gives total cylinder displacement per minut Internal combustion engines are usually rated at 15 per cent. to 20 per cen below the capacity of the cylinder as given above. Torrance and Ulbrich (*Power*, 1912) give the following **formulæ for builders' rating** in Americ

$$\text{Producer gas, b.h.p.} = \frac{d^2ln}{18{,}500} - 2.0 \qquad (80$$

$$\text{Illuminating gas, b.h.p.} = \frac{d^2ln}{15{,}700} - 2.0 \qquad (81$$

$$\text{Natural gas, b.h.p.} = \frac{d^2ln}{15{,}200} - 5.0 \qquad (82$$

$$\text{Blast-furnace gas, b.h.p.} = \frac{d^2ln}{21{,}000} - 5.0 \qquad (83$$

where d = diameter of cylinder, inches; l = stroke in inches; and n = re per. min.

516. The fuel consumption of gas engines on producers ranges fro 0.99 to 3 lb. per b.h.p.-hr. From 75 to 90 cu. ft. of gas pe b.h.p.-hr. are required, of approximately 150 B.t.u. per cu. ft.

517. Test of 300-h.p. Illmer 2-stroke cycle double acting horizont engine. (*Power*, May, 1913.) Duration of test, 33.5 hr.; coal, We moreland bituminous, 14,100 B.t.u. as fired; average b.h.p., 284; avers B.t.u. per cu. ft. of gas, 144; Producer efficiency, 67 per cent.; B.t.u. p h.p.-hr., 10,300; total coal per b.h.p.-hr. 1.14.

518. Fuel consumption, Ulbricht and Torrance (Power, 1912) gi average fuel consumption as below: (B.t.u. and cu. ft. per h.p.-hr.)

	50 b. h.p.			100 b.h.p.			Over 100 b.h.p		
	B.t.u.	cu.ft.	Eff.	B.t.u.	cu. ft.	Eff.	B.t.u.	cu. ft.	Eff
Water gas.....	10,690	35.2	23.8	10,160	33.4	25.0	10,160	33.4	25.
Carburetted gas.	10,690	18.1	23.8	10,160	17.2	25.0	10,160	17.2	25.
Coal gas.....	10,690	17.6	23.8	10,160	16.7	25.0	10,160	16.7	25.
Producer gas:									
anthracite....	10,380	82.6	24.5	9,630	76.6	26.4	9,600	76.3	26.
bituminous...	10,380	83.0	24.5	9,630	77.0	26.4	9,600	76.7	26.
coke.....	10,380	82.0	24.5	9,630	76.2	26.4	9,600	76.0	26.
lignite.....	10,380	77.5	24.5	9,630	71.8	26.4	9,600	71.6	26.
oil.....	10,380	68.7	24.5	9,630	63.7	26.4	9,600	63.5	26.
peat.....	10,380	73.6	24.5	9,630	68.3	26.4	9,600	68.0	26.
wood.....	10,380	80.6	24.5	9,630	74.8	26.4	9,600	74.6	26.
Blast-furnace gas	10,860	114.0	23.4	10,500	110.0	24.2	9,860	104.0	25.
Coke-oven gas..	10,690	22.0	23.8	10,160	20.9	25.0	10,160	20.9	25.
Natural gas avg..	10,380	12.2	24.5	9,420	11.0	27.0	9,320	10.9	27.

519. Test of a 310-h.p. engine, horizontal double-acting (Buckeye running on coke-oven gas, 560 B.t.u. per cu. ft., gave the following result

Load	B.h.p.	B.t.u. per h.p. hr.	Per cent. efficiency
½	165	13,000	18.5
¾	210	11,700	23.0
full	310	11,100	22.5

The B.t.u. per kw.-hr., with blast-furnace gas engines (Freyn, 1913), vari from 16,200 to 26,000, average 18,400; thermal efficiency 13.0 to 21.0 p cent., average 18.5.

520. Test of a 500-h.p. engine of the Borsig-Oechelhäuser 2-cyc type, on coke-oven gas (Junge, in *Power*) gave results as follows:

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I.h.p.	B.t.u. per b.h.p.	Per cent. of i.h.p. to pumps	I.h.p.	B.t.u. per b.h.p.	Per cent. of i.h.p. to pumps
616	8,660	10.8	488	9,642	14.2
627	8,650	11.1	474	9,761	15.5
574	8,650	11.4			

521. Test of a 600-h.p. engine, Körting 2-cycle type, gave these results: b.h.p. 616; pump work, 11.2 per cent. of total; mechanical efficiency, 0.78; lb. of coal per b.h.p-hr., 0.787.

522. Thermal efficiency of gas engines is given in Par. **518** and **519** in connection with some of the tables. Further data is given as follows by Diederichs:

Engine	Fuel	B.h.p.	Thermal efficiency	Authority
Otto.....	Illuminating gas.....	8	29.4	Meyer
Deuts.....	Suction producer, low grade soft coal.	.....	22.4	Meyer
Nürnberg...	Blast-furnace gas.....	750	24.6	Linde
Deuts.....	Anthracite producer.....	450	23.0	Josse
Güldner....	Suction anthracite producer.	29	23.2	Schroter

523. The overload capacity (Par. **515**) is generally 10 to 20 per cent. more than the rated capacity. The maximum capacity is limited by the dimensions of the cylinder and not by a variable cut-off. Maximum economy occurs at or near, maximum capacity.

524. Governing is accomplished by hit-or-miss, throttling or quality methods. **Hit-or-miss governing** is arranged with a movable pick-blade operating the gas inlet valve; it is now used only for low-grade agricultural engines. **Throttle governing** is employed on a great many engines of small and medium size, and consists simply of restricting both the gas and the air intakes, so that the suction stroke pressure is lowered, a smaller charge is taken in, and compression is reduced. **Quality or cut-off governing** consists of throttling the gas supply only, as the load drops. In this way no reduction of suction pressure occurs, but a reduction of gas in the charge only. The compression pressure is unaltered. This method is the best of the three, being more efficient at light load than throttling, and allowing better regulation than hit-or-miss.

525. Operation of a gas engine requires the same care as a steam engine, and a higher maintenance. Power-station gas engines are started by compressed air in most cases, although motor starters have been employed. Special valve gear is thrown into service, and the engine runs for a revolution or two as an air engine. **Before starting,** (a) the load must be off, (b) ignition system inspected and made ready in the retarded position, (c) lubricating oil feeds turned on, (d) fuel shut-off valve opened and (e) cooling water turned on. Failure to start may be due to (a) faulty ignition, (b) very abnormal mixture, either too rich or too lean, (c) broken valve rods or (d) closed fuel connections. **Ignition** should be adjusted to give a fairly sharp rise at the average load conditions, and the mixture should be a little leaner than theoretical proportions—say 15 to 20 per cent. **Shutting down** is best accomplished by, (a) cutting off fuel supply, (b) cutting out ignition, if on battery, and placing set in "retarded" position, (c) oil feed stopped, (d) cooling water shut off and jackets drained.

526. The cost of gas engines is given by the following formulæ (1920):

$$\text{Total cost} = 1{,}100 + 70.0\ (\text{b.h.p.}),\ \text{for 20 h.p. to 200 h.p.} \quad (84)$$

$$\text{Total cost of engines 300 h.p. up} = 2{,}000 + 66.00\ (\text{b.h.p.}) \quad (85)$$

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527. The maintenance and repair costs are approximately 42 per cent. to 55 per cent. of the net operating cost. For oil and supplies the cost is about double that of a steam plant.

528. Weight. The net weight of large tandem double acting types averages 680 to 740 lb. per kw. Moderate sizes of single-cylinder, single acting engines weigh from 200 to 300 lb. per b.h.p., the unit weight going up with the b.h.p.

PIPING

529. General requirements. As all pressures are light, standard pipe and fittings may be used throughout. **Expansion** must be provided for in the same manner as steam piping (Par. 369 to 372).

530. Gas piping from producer to scrubbers and purifiers should be cast iron with standard flanged joints, asbestos or metallic packing. In most cases it is advisable to line the piping between scrubber and producer with fire-brick. Explosion doors should be installed at intervals, and if the gas is dusty, ells should be replaced by tees where possible, to provide for raking and cleaning.

531. Water piping for supply to jackets, vaporizers and purifying apparatus may be of ordinary galvanized standard pipe. The discharge from scrubbers and purifiers is preferably of cast iron, on account of corrosive action.

532. Exhaust piping can be built of wrought-iron standard pipe, or cast-iron standard pipe; light riveted pipe is not advisable as it may collapse on the return wave of a muffler or exhaust pipe explosion. **Mufflers** for small engines are usually cast-iron pots; for large plants, concrete tunnels, with water in the bottom to cool and silence the exhaust, are frequently used.

533. The cost of piping varies from $6.00 to $12.00 per kw. of maximum rating of the plant, being much the same as for steam plants (1920).

PLANT ECONOMY AND DESIGN

534. The auxiliaries to be considered in the engine room are: compressors for starting; exciter units and cooling water pumps; station lighting. In the producer room the auxiliaries are: the blowers or exhausters, as the case may be; power for rotating ash table, producer body, or mechanical pokers if these are used; coal and ash handling apparatus; mechanical washers and tar extractors; scrubber and washer water-supply pumps.

535. The heat losses in a producer plant will be indicated by the following analysis. (Snell, "Power House Design.") Loss in producer and auxiliaries, 20 per cent.; loss in jacket water, 19 per cent.; loss in exhaust gases, 30 per cent., loss in engine friction, 6.5 per cent., loss in generator 0.5 per cent., total losses, 76 per cent., converted to electrical energy, 24 per cent.

536. The Willans line for the several main units should be plotted with kw. output and cu. ft. of gas as ordinates. On this curve should be superposed the gas used by auxiliaries, or if these are electric driven, their requirements should be subtracted from the gross output of the generators before plotting the Willans line. By taking the gas required at any load from this curve, and plotting for the load curve of the plant, the gas demand of the engine room is obtained. Similarly, an input-output curve for the producer can be drawn, between coal fired and gas generated; on this is superposed the gas or power demands of producer room auxiliaries and the standby coal. In conjunction with the engine-room gas demand curve this gives the coal demand for the station under load.

537. Power for auxiliaries. The power required for the blower or exhauster will be from 1 to 2.5 per cent. of the total horse-power of the producer. The horse-power requirements of washers are given in Par. **480**. The coal and ash handling system will not usually require more than 0.2 to 0.4 per cent. of the total horse-power; compressor equipment, not over 0.1 per cent. The total power requirements of the auxiliaries will be about 5 per

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cent. The **standby losses** of a producer banked 14 hr. in 24 are about 1.5 to 2.0 per cent. of the total.

538. Water consumption per h.p., for the plant will run from 5 to 8 lb. per kw-hr., at the switchboard for non-recovery plants, and 40 lb. per kw-hr. for recovery plants, using cooling towers in both cases.

539. Vertical vs. horizontal engines. Design practice in plants up to 2,000 b.h.p. will allow vertical engines; these usually are not built over 750 to 1,000 h.p. per unit. Above this size only horizontal engines are used.

540. Ammonia recovery. It is not worth while to attempt the recovery of ammonia from bituminous plants of less than 2,000 b.h.p., and then only when the load factor is above 25 per cent. Each ton of coal produces approximately 100 lb. of sulphate of ammonia; the sulphuric acid required is about 1 to 1 in weight ratio to the sulphate of ammonia. In cities, the recovery plant is practically out of the question on account of space requirements. Extra labor, the acid tower, extra repairs and the cost of bagging the sulphate must be taken into account.

541. The floor space required is from 5 to 8 sq. ft. per kw., or 3 to 4 times the floor space for a turbine plant. The producer room requires from 2.5 to 4 sq. ft. per kw.

542. The load factor should be high for a successful gas plant. The gas engine is not well suited for heavily swinging loads partly on account of its lack of much overload capacity.

543. The subdivision of generating units should be the same as for a steam plant—six to eight units if possible. For small units, up to 400 b.h.p. one reserve unit in 5 or 6 is sufficient; but for large units (which have never been brilliantly successful), one in four is necessary for continuity of operation. The **reliability** of the gas engine is still open to much question in very large units, but the units of moderate and small size are as reliable as steam engines, if given the same grade of attention.

544. Labor required is usually one man per engine above 750 h.p. and one man to four or five producers of good size and equipped with mechanical apparatus for feed and stoking. About one man for 1,000 to 1,200 h.p. of engine, and one man per 2,000 to 2,500 h.p. of producer, represent the average.

545. Total plant cost. The following data gives (1920) producer plant costs: For plants up to 4,000 kw.,

$$\text{Total cost} = 3{,}000 + 259.5\ (\text{kw.}) \qquad (86)$$

For plants larger than 4,000 kw.,

$$\text{Total cost} = 12{,}000 + 250 \times (\text{kw.}) \qquad (87)$$

The distribution of cost is given below for three cases, and is not much affected by size of plant.

Item	A	B	C
Buildings	16.50	11.4	14.95
Foundations			4.70
Producers and equipment	21.00	13.9	30.85*
Piping	3.25	5.2	
Gas engines	43.0	40.2	35.50
Generators	11.0	12.6	11.20
Switchboard	2.75	9.7	2.8
Service auxiliaries	2.50	7.0	
Total cost, per cent	100	100	100

*Includes piping and service auxiliaries.

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TESTING

546. The essential measurements for determining producer efficiency and capacity are:—(a) weight of coal per hr.; (b) proximate analysis, B.t.u. per lb. and moisture in coal; (c) cu. ft. of gas made; (d) temperature of gas, humidity; (e) calorific value and analysis. Additional data required for full information include: (f) weight of dry ash per hr.; (g) proximate analysis and B.t.u.; (h) wt. of steam per hr.; (j) wt. of vaporizer and scrubber water per hr., and temperatures; (k) h.p. required for blowers or exhausters and tar extractors or washers; (l) grains of dust per cu. ft. in gas.

For most purposes, only the efficiency of the producer itself is desired. For full details of tests, see Gas Power Committee reports, A. S. M. E.

547. The testing of gas engines is very similar to that of steam engines. The essential data are: (a) i.h.p.; (b) b.h.p. or kw. output and generator efficiency; (c) r.p.m.; (d) explosions per min., if hit-or-miss governed; (e) cu. ft. of gas per min.; (f) calorific power of gas per cu. ft. Desirable additional data include: (g) jacket water per hr.; (h) inlet and outlet jacket water temperatures; (i) gas, air and exhaust temperatures; (k) amount of lubricant. All physical dimensions of the engine should of course be taken.

548. The essential data for a plant test consist of kw.-hr. output at switchboard and coal used in producers; or cu. ft. of gas and calorific power, if coke oven, blast-furnace, natural, or illuminating gas is used.

549. For gas measurement the gas meter is chiefly used; the method of measuring the fall of a gas holder for volume should never be employed as the change of temperature ordinarily possible, entirely vitiates the accuracy. The Venturi meter furnishes an accurate and inexpensive measuring device if properly handled and kept clean in the throat.

550. Indicated h.p. is obtained by the usual indicator, but equipped with 0.5 in. area piston for this work.

551. The calorific value of gas can be obtained by the Junkers or other make of gas calorimeter. **Grains of dust per cu. ft.** are obtained by a special filter apparatus and test gas meter; the dust of a measured quantity of gas is collected and weighed. **Other measurements** are similar to those for steam engines (Par. **427**).

552. The duration of test should be about the same as for engine and boiler tests generally. For Venturi readings, a record is best, or very frequent readings, say once a minute. The producer test should preferably not be less than 24 hr. except with small producers intended for intermittent use; the longer the test the better.

553. For full calculation of results the heat balance is required. The Power Test Codes, A. S. M. E., furnish full data for the elaborate tests.

OIL POWER PLANTS

BY REGINALD J. S. PIGOTT

OIL ENGINES

554. The thermodynamics of the explosion cycle (Otto) type of oil engine are exactly the same as for gas engines (Par. **496** to **503**). **The constant-pressure cycle** (Brayton cycle), of which the **Diesel** is the principal example, has slightly different events. For the **four-cycle type**, the inspiration and compression strokes are the same, but are made upon air only; at the end of compression, the oil fuel is injected, and burned, in such a way as to maintain a practically constant pressure during the early part of the working stroke. Expansion and exhaust then follow as in the gas engine.

555. Thermodynamic equations. For the air card, or ideal cycle, p_b, t_b, and v_b are obtained as for the Otto cycle. Par 497 to 501., when burning fuel at constant pressure:

$$p_c = p_b \qquad (87) \qquad p_d = \left(p_c \frac{v_c}{v_d}\right)^{1.41} \qquad (91)$$

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$$t_c = t_b\left(1+\frac{Q_1}{c_p\ t_b}\right) \quad (88) \qquad t_d = t_a\frac{p_d}{p_a} \quad (92)$$

$$v_c = v_b\frac{t_c}{t_b} \quad (89) \qquad Q_2 = C_v(t_d - t_a) \quad (93)$$

$$v_d = v_a \quad (90) \qquad E = \frac{Q_1 - Q_2}{Q_1} \quad (94)$$

where p_a, p_b, p_c, p_d = inspiration, compression, combustion and release pressures, respectively, in lb. per sq. ft.; v_a, v_b, v_c, v_d = volumes in cu. ft. at beginning of compression, end of compression, end of combustion or beginning of expansion, respectively; t_a, t_b, t_c, t_d = absolute temperatures, at the same points in deg. Fahr.; Q_1 = heat added per lb. of gases, in B.t.u.; Q_2 = heat abstracted per lb. of gases in exhaust, in B.t.u.; E = thermal efficiency; C_v = specific heat at constant pressure.

556. The thermal efficiency would be the same as for the Otto cycle, if complete expansion occurred for the same compression pressures. But as expansion is always incomplete, the efficiency is less; this is more than offset by the much higher compression possible with the Diesel cycle.

557. Types. The types are the same as for gas engines; see Par. **502** and **503**.

558. Mean effective pressure of the Diesel type is given by

$$\text{M.e.p} = J\frac{[Q_1 - C_v t_a(Y^{1.41}-1)]}{144\ v_a\left[1-\frac{p_a^{0.71}}{p_b}\right]} \quad (95)$$

$$Y = 1+\frac{Q}{C_p t_a} \quad (96)$$

where J = Joule's equivalent, 777.5; C_v and C_p = specific heat at constant volume and constant pressure, respectively; t_a, v_a, p_a, p_b are the same as in Par. **554**.

Lucke gives the following usual m.e.p. for Otto types.

Kerosene		Gasolene	
Absolute compression pressure	Observed m.e.p.	Absolute compression pressure	Observed m.e.p
46	40	66	106
63	69	70	75
65	68	75	100
68	40	86	70
70	72	86	72
50	35	95	60
55	85	..	..

559. Speed and power. The speed is the same as for gas engines of the same power (Par. **511**). For indicated and b.h.p. see Par. **512**.

560. Kerosene engines of the Mietz and Weiss and Hornsby-Akroyd types are built in sizes up to 250 h.p. and operate in the same general manner as gas engines, the fuel being pumped in and vaporized in a hot tube, hot bulb, or vaporizing chamber. The hot tube and the hot bulb are kept warm by being left unjacketed, and by the combustion of a portion of the charge in the hot bulb chamber. Compression forces up the temperature of the charge enough for ignition to take place. Kerosene engines are the least efficient of the oil engines.

561. Gasolene engines are practically unused for power-station purposes, on account of expensive fuel, and low relative economy, except for 1½ to 5 kw. house or farm lighting sets.

562. The crude oil engine is arranged like the kerosene engine, except that more careful arrangements must be made for preheating the oil for vaporization, and in most cases, the air also. Exhaust gas jackets are generally used for the purpose of providing the necessary heat.

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563. The Diesel engine is now the most important of the oil engines on account of its remarkable efficiencies. It is built in both two-cycle and four-cycle types, and practically always vertical, single acting. It requires separate compressed-air starting sets, at about 1,000 lb. per sq. in. pressure. In the two-cycle type, separate air pumps (cylinders driven from the cross-head) are employed, as well as the fuel pump, which is always necessary.

564. Weights. The Diesel and the Junkers engines are the heaviest of prime movers, running from 400 to 600 lb. per b.h.p. The enormous weight is due chiefly to the heavy pressures, 500 lb. per sq. in. being an ordinary compression, with safe design allowance up to 1,000 lb. per sq. in. to safeguard against breakage due to preignition.

565. The capacity of oil engines is based on cu. ft. of cylinder displacement, as for gas engines (Par. **515**).

566. Builders' rating. Ulbricht and Torrance (*Power*, 1912) give average practice in builders' rating (for oils and distillates), as

$$\text{b.h.p.} = \frac{d^2\, ln}{21{,}875} - 0.75 \qquad (97)$$

where d = cylinder diameter, in in; l = stroke in in. n = r.p.m. The rating is about 10 to 20 per cent. less than the ultimate capacity.

567. The fuel consumption is poorest for the gasolene and kerosene engines, running from 13,000 to 15,600 B.t.u. per b.h.p.-hr.; 9,400 to 10,000 B.t.u. per b.h.p. hr., for American Diesel engines. The German Diesel and Junkers engines run as low as 7,100 to 8,500 B.t.u. per b.h.p. hr. All figures are for full load. These figures correspond to 0.65 to 0.7 lb. of gasolene or kerosene per b.h.p.-hr.; 0.48 to 0.52 lb. of oil for American Diesels; 0.37 to 0.44 for German Diesel and Junkers Engines. Fuel consumption decreases with size.

568. Test of Falk kerosene oil engine (H. D. Wile, Elec. World, 1913)

Cooling water, lb. per hr.			632	445	391	244
Inlet temperature, deg. Fahr.			47.5	44	71	47.5
Outlet temperature, deg. Fahr.			106	123	157	182
Rev. per min.			448	448	449	446
B.h.p.			9.05	9.05	8.73	9.03
Indicated h.p.			11.04	11.31	10.65	11.84
Mechanical efficiency, per cent.			82	80	82	76
Kerosene, lb. per b.h.p.-hr.			1.14	1.09	0.98	1.0
Thermal efficiency			11.2	11.7	13.1	12.8
Angle ignition, deg.				34	38	41
Rev. per min.				446	450	442
B. h.p.				8.73	9.05	8.7
Indicated h.p.				11.7	10.65	12.0
Mechanical efficiency				77	82	75
Kerosene, lb. per b.h.p.-hr.				0.97	0.98	0.9
Thermal efficiency				13.2	13.1	13.4
Mixed water-kerosene, per cent.				34.4	62.8	85
Rev. per min.				442	440	444
B.h.p.				8.7	8.7	8.7
Indicated h.p.				12.3	11.7	11.4
Mechanical efficiency				71	74	76.7
Kerosene, lb. per b.h.p.-hr.				1.06	1.14	1.1
Thermal efficiency				12	11.1	10.5
B.h.p.	4.2	5.5	7	8.73	10.3	11.9
Indicated h.p.	6.4	7.5	9.17	11.2	12.5	14.3
Rev. per min.	457	457	450	448	437	436
Mechanical efficiency	66	74	76	77	82.5	82.8
Cooling water, lb. per hr.	236	290	306	262	309	304
Kerosene, lb. per b.h.p.-hr.	1.55	1.26	1.05	0.93	0.87	0.9
Thermal efficiency	7.3	10.1	12.1	13.8	14.7	13.6
Maximum pressure, lb. per sq. in.	68	94	124	170	206	242

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	Number of Test					
	1	2	3	4	5	6
Duration of test, hours	3.00	3.00	3.00	3.00	3.00	3.00
Switchboard reading, kw.		37.42	80.23	117.5	160	180.1
Compressor motor, gross kw.		6.9	9.09	8.93	10	11.4
Net kw. output		30.52	71.14	108.57	150	168.7
Efficiency of generator, per cent.		85	87	90	92	92.5
Net b.h.p. load	2.25	49.7	111.39	162.97	219.63	245.6
Speed, rev. per min.	171.1	169.1	167.4	164.4	164.8	161.9
Cooling water/hr., lb.	3,187	3,037	4,875	6,300	4,537	5,175
Jacket inlet temperature, deg. Fahr.	61.8	62.4	61.9	62.6	61.7	66.7
Jacket outlet temperature, deg. Fahr.	115.3	127.9	115.5	118.9	156.6	173.1
Injection air pressure, atmospheres	39	45.6	56	59	66	77
Fuel oil-pounds per net kw. hr.		1.25	0.7555	0.681	0.646	0.644
Fuel oil-pounds per net b.h.p.-hr.		0.769	0.482	0.454	0.441	0.444
Fuel oil-gals. per 100 net b.h.p.-hr.		10.8	6.8	6.4	6.2	6.2
Thermo-dynamic effic. based upon net useful output, per cent.		17.4	27.8	29.5	30.3	30.2

570. The efficiency of gasolene engines at full load varies from 18 per cent. at 10 b.h.p. per cylinder, to 20 per cent. at 22 to 32 b.h.p. per cylinder; **kerosene engines,** 1 to 2 per cent. less; **American Diesel engines,** from 26 per cent. at 60 b.h.p. per cylinder end, to 27 per cent. at 100 b.h.p. and over, per cylinder end; **German Diesels,** from 33 per cent. at 60 b.h.p. per cylinder end, to 36 per cent. at 100 h.p. All figures are at full-load.

571. The overload capacity of oil engines is not more than 10 to 20 per cent. above the rated capacity.

572. Governing in oil engines is chiefly by throttling the oil supply to the cylinder. The Mietz and Weiss kerosene engine governs by the hit-or-miss principle on the oil pump.

573. Ignition in some of the kerosene engines, and all of the gasolene engines, is by electric spark, usually make-and-break. Some of the kerosene engines operate with hot bulb. The Diesel types and most of the heavy oil types ignite by means of the heat due to high compression.

574. The operation of the kerosene and other low-compression oil engines is practically the same as for gas engines. The hot-tube systems require occasional removal for cleaning of carbon deposit, and clearing the oil holes. The Diesel engine, however, requires the highest class of operating labor, on account of the high pressures employed, and the lubrication difficulties. These objections are reflected in the lower efficiency of American engines compared with English or German types, because the compression pressures have been reduced to relieve pressure and lubrication troubles, and thus obviate the use of such highly skilled labor.

575. The cost of internal combustion engines is given as follows:

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Gasolene, up to 75 h.p., throttle governed,

Total cost = 253.0 + 59.2 (b.h.p.) (dollars) (99

Oil engines, up to 400 h.p.,

Total cost = 356 + 85 × (b.h.p.) (dollars) (100

Diesel engines, from 100 to 1,000 h.p., approximately (price varies ver widely),

Total cost = 58.0 (b.h.p.) + 2,000 (dollars) (101

Stott, Pigott, and Gorsuch, A.I.E.E. *Proceedings*, June, 1914, give 95.0 per kw. for all sizes of Diesel engines complete with generators. This is du to the fact that weight per kw. *increases* with size. The price in June, 192 was $150.00 per kw.

576. Test of a low-compression heavy oil engine. (A. A. Potter and W. W. Carlson, *Elec. World*, 1913)

Cylinder diameter, in.	16 $\frac{1}{4}$
Length of stroke, in.	24
Kind of fuel	Solar oil
Specific gravity at 60 deg. Fahr.	0.8145
Deg. Beaumé	42.0
Lb. per gal.	6.79
Heat units per lb., high	17,240
Heat unit per lb., low	16,322
Heat units per gal.	117,100

Data and results	Number of test		
	1	2	3
Duration of heat, hours	3	1	1
Barometer, in.	26.95	26.94	26.9
Speed of engine, rev. per min.	183.5	201.2	202.0
Mean effective pressure	75.9	37.1	27.3
Indicated h.p.	85.6	45.5	34.0
B.h.p: Average	73.5	39.70	20.2
Mechanical efficiency, per cent	85.8	87.4	59.4
Fuel used, total lb.	222.75	50.1	42.5
Fuel used per i.h.p. per hour, lb.	0.868	1.10	1.2
Fuel used per b.h.p. per hour, lb	1.010	1.26	2.1
Heating value of fuel consumed:			
Per b.h.p. per hour, b.t.u.	17,400	21,750	36,200
Temperature of cooling water, deg. Fahr.			
Inlet	82.25	79.0	84.2
Outlet	164.0	133.0	125.5
Rise	81.75	54.0	41.2
Cooling water used per hour:			
Total, lb.	1,775	2,868	2,712
Per b.h.p., lb.	24.2	72.2	134.2
Thermal efficiency, per cent.	14.62	11.7	7.0

Heat distribution per lb. of fuel	1		2		3	
	B.t.u.	Per cent.	B.t.u.	Per cent.	B.t.u.	Per cent
Converted into i.h.p.	2,935	17.0	2,315	13.4	2,036	11.3
Converted into b.h.p.	2,520	14.26	2,020	11.7	1,210	7.0
Friction and losses	415	2.40	295	1.7	826	4.7
Losses in jacket water	1,955	11.32	3,090	17.9	2,635	15.2
Losses in exhaust, radiation, etc.	12,350	71.68	11,835	68.9	12,569	73.4

577. The cost of piping for oil plants, per installed kw., ranges fro $1.20 to $3.85 (1920).

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PLANT DESIGN

578. General. What has been given in Par. **394** to **414** can be applied in principle to the oil plant. But inasmuch as the only auxiliaries are the starters, jacket pumps and air compressors for starting, the problem is much simpler, and the economy of the plant is much more nearly that of the main unit.

579. Plant costs. The oil storage tanks require approximately 0.06 to 0.08 gal. capacity per kw. All other auxiliaries, including crane, oil pumps, air compressor and compressed air tanks, cost from $4.00 to $10.00 per kw. of rated capacity, installed. The total costs will range as follows, per kw.:

	High	Low
Diesel engine and generator	$180.00	$160.00
Building	40.00	16.00
Tanks	15.00	5.00
Auxiliaries	10.00	4.00
Piping	3.80	1.20
Totals	248.80	186.20

There are no plants in this country much larger than 1,500 kw. in total capacity.

TESTING

580. The testing of oil engines is exactly similar to the testing of gas engines, except that weight of oil per hr. is substituted for cu. ft. of gas per hr. All other data and instruments required are the same.

POWER PLANT BUILDINGS AND FOUNDATIONS

BY REGINALD J. S. PIGOTT

581. The building housing any kind of power plant should be entirely fireproof. In many cases, no fire insurance is carried, and therefore all wood and other unnecessary combustible should be kept out of the structure.

582. The approved constructions are: (a) Steel structure, brick walls, concrete, slate or tile roof. For small low-grade plants corrugated iron may be employed to a very limited extent. (b) Steel framework, walls and roof concrete. (c) Reinforced concrete throughout. Type (c) is exploited chiefly in the hydroelectric plants; type (a) is the most widely employed. Concrete **foundations,** for all work, are practically universal.

583. The general arrangement of engine rooms in the older plants and the most modern, is parallel to the boiler room. About 8 years ago the sudden increase in capacity of the turbine without much increase in size made the use of cross firing aisles necessary, to get in enough boilers. But the underfeed stoker has so increased the forcing capacity of the boiler that this is now unnecessary.

584. In gas-producer plants, the producer room is generally arranged parallel to the engine room, although it may be entirely separate and some distance away, as in some recovery plants.

585. The coal bunkers in larger power plants are of steel framing with concrete arch lining. For moderate size plants, and for outdoor bunkers of producer plants, the suspended type, catenary-curve bunker is widely used; also steel with concrete lining. Hoppers and chutes for coal, are made of plate steel or cast iron; ash hoppers, of plate steel lined with red brick, or reinforced concrete.

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586. Brickwork for power-station buildings varies about as giv below. May, 1920.

Heavy basement work, labor cost, only,	**$15.00 to $20.00 per M.**
18 in. walls	**17.00 to 21.50 per M.**
13 in. walls	**20.00 to 23.50 per M.**
18 in. wall, faced on one side with pressed brick	**25.00 to 30.00**
18 in. wall, faced on both sides with pressed brick	**35.00 to 41.00**
13 in. wall, faced on one side with pressed brick	**30.00 to 36.50**

This is for straight wall work. For work much cut up by windows a corners, these prices must be increased. Common red brick costs abo $21.00 per M delivered in or near cities.

587. Concrete. The following approximate cost for concrete applied 1920.

Item	Per cubic yard	
	Range	Averag
Mass foundations	$7.20 to 10.10	$12.50
Conduits and sewers	9.00 to 28.80	17.00
Tunnels, subways	10.80 to 75.00	27.00
Reinforced retaining walls	21.50 to 27.00	24.00
Reservoirs, filters	10.80 to 41.00	19.00
Tanks, standpipes	7.20 to 36.00	21.50
Buildings, total structures	14.50 to 47.00	25.00
Walls in building construction	21.00 to 45.00	31.50
Encasing structural steel in concrete	25.00 to 37.00	33.00

588. Structural steel for building purposes costs from $105.00 $270 per ton, erected. For any amount over 200 tons, it should n ordinarily exceed $125.00 per ton. May, 1920.

589. Building foundations are made almost exclusively of mass co crete (Par. **587**).

590. The bearing power of soils for computing the proper spread footings is given below.

Soil	Tons per sq. ft.	Remarks
Good solid natural earth	4.0	New York Building Laws
Pure clay, 15 ft. with no admixture of foreign substances except gravel.	1.75	Chicago Building Ordinanc
Dry sand, 15 ft. thick, no admixture of foreign substances.	2.0	Chicago Building Ordinanc
Clay and sand mixed	1.5	Chicago Building Ordinanc
Hard rock on native bed	2.50	Richey
Ledge rock	36.0	Richey
Hard-pan	8.0	Richey
Gravel	5.0	Richey
Clean sand	4.0	Richey
Dry clay	3.0	Richey
Wet clay	2.0	Richey

591. For making concrete in any quantity, machine mixing alw pays, both in first cost and in reliable quality. **Form work** is usua of 1.25-in. tongued and grooved, short-leaf yellow pine lumber dressed o side, with 2 in. x 4 in. rough spruce or yellow pine studs and bracing the greater part; 4 in. x 4 in. studs, and larger, are used only wh necessary.

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592. Loads on Foundation

(Chicago Building Ordinances)

Foundation	Tons per sq. ft.	Foundation	Tons per sq. ft.
crete.....	4.0	Iron rails in concrete...	6.0
ndation piers, dimension ne.	5.0	Steel rails in concrete...	8.0
k piers in cement.....	9–12.5	Piles.....	12.0

3. **Machinery foundations** are generally of mass concrete, as for lings. But lately the demands for condenser and auxiliary space r steam turbines have forced the use of **structural steel foundations.** e is no objection objection to this, provided the turbine is properly ıced and the maximum permissible deflection of about 0.02 in. is not ded. Foundations should extend up to 1 in. or ½ in. below the bottom of the machine base to be set; and when the latter is lined up, the whole ld be grouted with cement grout, mixed 1 : 2, of cement and sand. ndation bolts are now seldom set from templates, but are accurately ed in the forms by drawing dimensions. Each bolt is mounted in a sleeve large enough to allow a play of at least one diameter for taking of inaccuracies in the casting and in the setting. With some turbines, olts whatever are needed.

4. **Drainage** should if possible be arranged for by placing the whole on above sewer or tide-water level, so that gravity flow from sumps and is possible. Where this cannot be done, suitable reservoir sumps t be provided, emptied by ejectors or pumps, float controlled. Galed iron or cast-iron roof leaders may be employed, with cast-iron soil in the ground, or glazed clay tile pipe.

5. **Lighting and ventilation.** The use of all-glass monitors is the desirable way of lighting and ventilating plants. The rolled steel on windows and monitors now produced have rendered easy the problem reproof, permanent window and ventilator fixtures. The operating es should be arranged for quick opening and closure, to provide for n protection. The continuous sash for monitor use is the latest device is line. Care should be taken to make windows rain- and snowproof, to allow opening for ventilation without letting in rain during ordinary ns.

6. **Lighting by daylight** is accomplished by the monitors above ioned and by high side windows in some cases. The night illumination st cases is by incandescent lamp. The arc and Nernst lamps are generundesirable; the mercury vapor lamp is very successful where used, and least injurious to eyesight, but there is much general objection to the of the light. The usual demand for illumination in a power station ake from 0.2 to 0.5 per cent. of the output.

7. **Fire risks** in well constructed plants are exceedingly low; in many e largest plants, no insurance against fire is carried. The use of wood or other inflammable structures, makes insurance imperative.

8. **The cost of buildings** for various types of power plant is given in 411, 545 and 579 per kw. of capacity. The cost per cu. ft. of contents s variable, and runs from $0.40 to $0.65. May, 1920.

HYDRAULIC POWER PLANTS

BY ARTHUR T. SAFFORD

ulting *Hydraulic Engineer, Member, American Society of Civil Engineers, Member, American Society of Mechanical Engineers*

HYDRAULICS

9. **Pressure and depth.** Water is but slightly compressible, therefore pressure, P, is for all practical purposes directly proportional to the h, H, and can be represented by a diagram as shown in Figs. 46 to 49.

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The total pressure on any submerged surface is equal to the ar of the pressure diagram (*abc*, Fig. 46; *decb*, Figs. 47 and 48) and the centre pressure passes through its centre of gravity, *G*, perpendicular to the su merged surface. The moment of the pressure about *c* is (Fig. 49),

$$M = Py \qquad \text{(ft-lb.)} \qquad (10$$

The pressure in lb. per sq. in. at any point is

$$p = 0.433 \times \text{Depth} \qquad (10$$

The pressure is always normal to the submerged surface. The total pr sure exerted on a submerged body is

$$P = 62.4HA \qquad \text{(lb.)} \qquad (10$$

wherein H is the depth of water in feet over the geometrical centre of t body and A is the area of the surface in sq. ft.

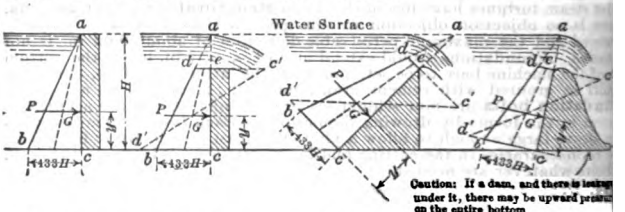


FIG. 46. FIG. 47. FIG. 48. FIG. 49.

600. Possible upward pressure under dams. If the structure is dam and there is leakage under it there may be upward pressure over t entire bottom. If there is no leakage then there will be no upward pressu The truth in any given case probably lies between these two extremes a the foundations and underlying material must be carefully studied to ma a proper design.

601. The dynamic properties of water in motion are theoretica the same as those of falling bodies *i.e.*:

$$V = \sqrt{2gh} = 8.02\sqrt{h} \qquad \text{(ft. per sec.)} \qquad (10$$

where $g = 32.16$.

Actually this formula is rarely exact and expressions based upon it m be modified by empirical coefficients.

602. The quantity of water passing a given point in a unit of ti is equal to the product of the net cross-sectional area taken perpendicular the line of flow and the mean velocity in that time parallel to the line of flo This may be expressed by the equation

$$Q = AV \qquad \text{(sec-ft.)} \qquad (10$$

If A is the area in square feet, V the velocity in feet per second, then is the quantity in cu. ft. per sec., or, in its briefer form, second-feet. T in the United States is now the common expression in water-power practi for flow of streams, capacity of canals and raceways and discharge of wat wheels.

603. At every section of a continuous and steady stream the to energy is constant; whatever head is lost as pressure is gained as veloci This is known as **Bernoulli's theorem**, and in terms of head can be expres as follows: Total head = velocity head + pressure head + head due to e vation = constant; or in every stream section,

$$H_T = h_v + h_p + h_e = \frac{V^2}{2g} + \frac{p}{y} + h_e \qquad \text{(ft.)} \qquad (10$$

where y is the constant to reduce lb. per square inch to head in feet, or 0.43

In order to make this equation of practical application, a term representi the head lost in overcoming friction, h_λ, must be added on the right-hand si of the equation. This formula, properly modified to include the effect

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:tional resistances, is the basis of all empirical formulas for the flow of :ter.

604. Power and energy. The potential energy of water held in reserve its weight multiplied by the net available distance through which it can l in the performance of work. As power expresses the rate of doing the work, s convenient to deal with the flow of water in cu. ft. per sec. falling through iven vertical distance in feet. Power $= 62.4QH$ ft-lb. per sec., where s the flow in cu. ft. per sec., and H the vertical distance or "head" in feet d 62.4 is the weight in pounds of 1 cu. ft. of water.

$$\text{Horse-power} = \frac{62.4QH}{550} = \frac{QH}{8.8} \qquad (108)$$

This is the maximum horse-power that might be obtained from Q cubic t of water per second falling a distance H feet, assuming an efficiency of nsformation of energy of 100 per cent. This expression multiplied by known efficiency of a water wheel will give the power at the water-wheel ft. Ordinarily $QH/11$ or $QH/12$ will give approximately the net water rse-power, corresponding respectively to efficiencies of 80 per cent. and 73.3 cent.

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605. Orifices employed as meters, are limited in use; experimentally y have given very consistent results, but in practice these results often not be reproduced with sufficient accuracy for precise work. Orifices of atively small sizes, of regular shapes (usually round or rectangular), with efully made edges, and used with l contraction of the jet, have been efully experimented upon and may used with confidence provided there practically no velocity of approach s than 0.5 ft. per sec.).

606. The flow of water through an ifice (Fig. 50) in a vertical wall ex-ssed in cubic ft. per sec. is

$$Q = CAV = CA\sqrt{2gh} \qquad \text{(cu. ft. per sec.)} \quad (109)$$

ere A is the area of the opening in uare feet, h the head in feet measured m the surface of the water to the cen- of the opening, and C is the coeffi- nt of discharge which depends on form of the orifice. For sharp-edged ifices, 4 sq. ft. or less in area, with full ntraction of the issuing stream (Fig.), discharging under heads from about o 20 times the depth of the orifice ctically no velocity of approach), a lue of C may be taken as 0.6. If the ifice is large and the head acting is all, the exact or integral form of the uation* must be used when C is taken 0.6. For high heads and relatively all orifices this is not necessary. If contraction is even partly suppressed results are unreliable; if wholly suppressed the orifice becomes a short be or nozzle and the coefficient varies greatly, depending on the shape d proportions; but always more than 0.6 (see Par. **635**).

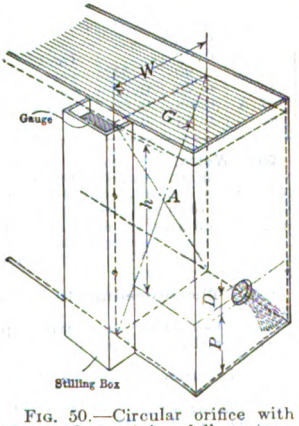


FIG. 50.—Circular orifice with sharp edges, giving full contraction.

607. In treating head gates and sluice gates as orifices, the forms of ss-section, the channel of approach and that leading away from the ifice, and the velocity of approach are all very important; these factors odify any computed discharge based upon the opening and observed head.

* Water Supply and Irrigation Paper No. 200.

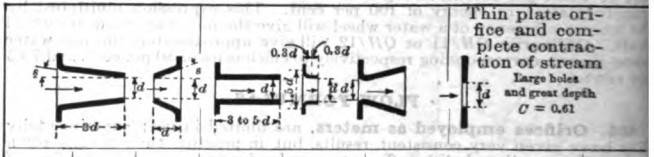
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The coefficient of discharge for gates on the basis of their cross-sectional area and the head measured above and below them may vary all the way from that of a standard sharp-edged orifice (0.6) to over 1.0 if there is much velocity of approach. For these reasons, if head gates or sluice gates are to be used as measuring devices they should be given their own rating by some independent method of measurement.

608. Weisbach's Coefficients

$$C \text{ in } Q = C\frac{\pi d^2}{4}\sqrt{2gh} \qquad (109A$$

wherein C is a coefficient which depends on the form and head h acting on orifice, Q is given in cubic feet per sec. when h and d are measured in feet, h is head in feet above centre of orifice; and d is diameter of orifice in feet.



S. deg.	C	C	Inlet slightly round $C=0.90$	Depending upon smoothness surface $C=0.96$ to 0.99	Depending on the length and velocity $C=0.96$ to 1.5	d	h = 1.148	h = 1.969
							C	C
0.	0.97	0.54				0.0144	0.68	0.66
5.75	0.95	.....				0.0328	0.64	0.63
11.25	0.92	.....	Inlet very round $C=0.97$			0.0656	0.63	0.62
22.5	0.90	0.55				0.0984	0.62	0.61
45.	0.75	0.58				0.1312	0.614	0.607
67.5	0.68	0.60						
90.	0.63	0.63						

609. Weirs,* if properly constructed and used with faithful regard to reproducing the exact conditions which obtained when the experimenter derived his formula, should give good results. Some extraordinary results have been obtained because these precautions were not observed; and weir measurements unless standardized will gradually lose their hold. A weir installation in a power plant must necessarily cut down the available head by roughly 3 ft. For this reason the weir should be used only for testing and not for operating.

610. "The procedure to be followed in weir measurements comprises:†

(*a*) Constructing and setting up the weir and the gage for measuring the head; reproducing, if possible, the experimental conditions of the formula to be used.

(*b*) Measuring the length of the crest and determining its irregularities if any.

(*c*) Taking a profile of the crest if not sharp-edged.

(*d*) Determining by actual measurements the cross-sectional area of the channel of approach.

(*e*) Establishing by leveling the relative elevations of the crest of the weir, and the zero of the gage.

(*f*) When the desired regulation of flow is established, determining the head by hook gage or other observations at intervals as frequent as the conditions require.

* For the most extended compilation and examination of existing weir data Water Supply and Irrigation Paper No. 200 (Weir Experiments, Coefficients, etc., by R. E. Horton) should be consulted.

† Hughes and Safford, "Hydraulics;" New York, MacMillan Co., 1911; page 196.

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(g) If possible, measure the actual velocity in the channel of approach by a current meter or some other direct method; and

(h) Compute the discharge by the formula selected. Three of these operations require especial consideration, viz.: construction and setting, the measurement of the head, and the selection of the formula."

FIG. 51.—Weir with end contractions.

FIG. 52.—Weir with end contractions suppressed.

611. **"Construction and setting of weirs."** * In order to eliminate as far as possible factors for which precise allowance cannot be made, the construction and setting should meet the following conditions:

(a) A sharp-crested weir with complete crest contraction should be used.

(b) The crest should be level, and its ends vertical.

* Hughes and Safford, "Hydraulics;" New York, MacMillan Co., 1911.

612. Standard Weir Formulas (Par. 613 to 621)

Experimenter	Formula (cu. ft. per sec.)	Limits of head recommended (ft.)	Distance of crest above bottom (ft.)	Correction for end contraction	Correction for velocity of approach	
					Suppressed weir	Contracted weir
Fteley & Stearns	$Q = 3.31L\sqrt{H^3} + 0.007L$	0.07 to 0.50	At least 2.0	$L = (L - \frac{NH}{10})$ *	$H = (h + 1.50h_v)$	$H = (h + 2.05h_v)$
Francis	$Q = 3.33L\sqrt{H^3}$	0.50 to 2.00	At least 3 times the observed head	$L = (L - \frac{NH}{10})$	$\sqrt{H^3} = (h - h_v)^3 - h_v^3$	.....
Hamilton Smith	$Q = (C_o \text{ or } C_s)\frac{2}{3}L\sqrt{2g}H^{\frac{3}{2}}$	0.10 to 1.70	At least 3 times the observed head	Use proper coefficient	$H = (h + 1 - \frac{1}{2}h_v)$	$H = (h + 1.4h_v)h_v$
Bazin**	$Q = mLh\sqrt{2gh}$	0.20 to 2.00	.....	.....	.....	.....

* Fteley & Stearns found that in this expression $\frac{H}{10}$ was not constant but varied with perfect contraction from $0.061H$ to $0.124H$, H being equal to $(h + ah_v)$; a being equal to 1.5 and 2.05 according to form of weir.

** *For suppressed weirs only.* m being a coefficient including effects of crest contraction and velocity of approach.

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(*c*) The end contractions should be complete, or, if suppressed, entirel; suppressed.

(*d*) The upstream face should be vertical; the downstream face so designe that the nappe has free overfall.

(*e*) Free access for air under the nappe should be made certain.

(*f*) The weir should be set at right angles to the direction of flow.

(*g*) The channel of approach should be straight for at least 25 ft. abov the weir, of practically uniform cross-section and of slight slope (preferabl none).

(*h*) Screens of coarse wire or baffles of wood should be set in the channe if necessary, to equalise the velocities in different parts of the channel, bu not nearer the crest than 25 ft.

(*i*) The channel of approach should have a large cross-sectional area i order to keep the velocity of approach low."

A weir with complete end contractions is shown in Fig. 51; suppressed en contractions are shown in Fig. 52.

613. Francis formulas. The best known formulas are those of James B Francis and M. Basin. The Francis formulas are strictly applicable only t **vertical, sharp-crested weirs** with free overfall and either with no end con tractions ("suppressed weir"), or with complete end contractions and: (*a*) when the length of the weir is at least 5 ft.; (*b*) when the head (H) is no greater than one-third the length (L); (*c*) when the head is not less than 0. ft. nor more than 2 ft.; (*d*) when the velocity of approach is 1 ft. pe second or less; (*e*) when the height of the weir crest above the bottom of th channel of approach is at least three times the head. For tabulation o standard formulas see Par. **612**.

614. Smith's formulas. For **short weirs** (shorter than 5 ft.) th experiments and studies made by Hamilton Smith, Jr., afford the bes guide (See Smith's weir coefficients, Par. **620**).

615. Basin's formula. The best weir experiments abroad are those o M. Basin whose general formula is $Q = mLh\sqrt{2gh}$ for suppressed weirs only At about 1.0 ft. depth on the crest, with no velocity of approach, th results from his standard 8.56-ft. (2-meter) weir are practically those o James B. Francis' standard 10-ft. weir (See Par. **621**).

616. Fteley and Stearns' formula. For heads from 0.07 to 0.5 ft. th Fteley and Stearns formula* $Q = 3.31L\sqrt{H^3} + 0.007L$ is recommended.

617. Weir discharge tables. The following table of discharges for weir without end contractions, and velocity head is given for heads from 0.00 t 2.98 ft. and includes figures from the Fteley and Stearns formula up to 0. ft. and the Francis formula from 0.5 ft. to 2.98 ft. The quantity o water is given in cu. ft. per sec., per foot of weir, with complete con traction on the crest, and no end contractions. $Q = 3.31L\sqrt{H^3} + 0.007L$ fo depths up to 0.5 ft. and $Q = 3.33L\sqrt{H^3}$ for depths above 0.5 ft.; the velo city due to the head is computed by formula, Vel. $= \sqrt{2gh}$.

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* Fteley and Stearns, in "Sudbury River Experiments" (page 84) stat that this formula is based upon experiments in which the depths on th weir ranged from 0.07 to 1.63 ft. *Trans.* Amer. Soc. Civil Eng., Vol. XII.

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H (ft.)	Quan. (sec-ft.)	Velo. (ft. per sec.)	H (ft.)	Quan. (sec-ft.)	Velo. (ft. per sec.)	H (ft.)	Quan. (sec-ft.)	Velo. (ft. per sec.)
0.00	.....	.....	0.50	1.18	5.67	1.00	3.33	8.02
.02	.02	1.13	.52	.25	5.78	.02	.43	8.10
.04	.03	1.60	.54	.32	5.89	.04	.53	8.18
.06	.06	1.96	.56	.39	6.00	.06	.63	8.26
.08	.08	2.27	.58	.47	6.11	.08	.74	8.33
0.10	0.11	2.54	0.60	1.55	6.21	1.10	3.84	8.41
.12	.14	2.78	.62	.63	6.32	.12	.95	8.49
.14	.18	3.00	.64	.70	6.42	.14	4.05	8.56
.16	.22	3.21	.66	.79	6.52	.16	.16	8.64
.18	.26	3.40	.68	.87	6.61	.18	.27	8.71
0.20	0.30	3.59	0.70	1.95	6.71	1.20	4.38	8.79
.22	.35	3.76	.72	2.03	6.81	.22	.49	8.86
.24	.40	3.93	.74	.12	6.90	.24	.60	8.93
.26	.45	4.09	.76	.21	6.99	.26	.71	9.00
.28	.50	4.24	.78	.29	7.08	.28	.82	9.07
0.30	0.55	4.39	0.80	2.38	7.17	1.30	4.94	9.14
.32	.61	4.54	.82	.47	7.26	.32	5.05	9.21
.34	.66	4.68	.84	.56	7.35	.34	.16	9.28
.36	.72	4.81	.86	.66	7.44	.36	.28	9.35
.38	.78	4.94	.88	.75	7.52	.38	.40	9.42
0.40	0.84	5.07	0.90	2.84	7.61	1.40	5.52	9.49
.42	.91	5.20	.92	.94	7.69	.42	.63	9.56
.44	.97	5.32	.94	3.03	7.78	.44	.75	9.62
.46	1.04	5.44	.96	.13	7.86	.46	.87	9.69
.48	.11	5.56	.98	.23	7.94	.48	6.00	9.76
1.50	6.12	9.82	2.00	9.42	11.34	2.50	13.16	12.68
.52	.24	9.89	.02	.56	11.40	.52	.32	12.73
.54	.36	9.95	.04	.70	11.46	.54	.48	12.78
.56	.49	10.02	.06	.85	11.51	.56	.64	12.83
.58	.61	10.08	.08	.99	11.57	.58	.80	12.88
1.60	6.74	10.14	2.10	10.13	11.62	2.60	13.96	12.93
.62	.87	10.21	.12	.28	11.68	.62	14.12	12.98
.64	.99	10.27	.14	.42	11.73	.64	.28	13.03
.66	7.12	10.33	.16	.57	11.79	.66	.45	13.08
.68	.25	10.40	.18	.72	11.84	.68	.61	13.13
1.70	7.38	10.46	2.20	10.87	11.90	2.70	14.77	13.18
.72	.51	10.52	.22	11.01	11.95	.72	.94	13.23
.74	.64	10.58	.24	.16	12.00	.74	15.10	13.28
.76	.77	10.64	.26	.31	12.06	.76	.27	13.32
.78	.91	10.70	.28	.46	12.11	.78	.43	13.37
1.80	8.04	10.76	2.30	11.61	12.16	2.80	15.60	13.42
.82	.18	10.82	.32	.77	12.22	.82	.77	13.47
.84	.31	10.88	.34	.92	12.27	.84	.94	13.52
.86	.45	10.94	.36	12.07	12.32	.86	16.11	13.56
.88	.58	11.00	.38	.23	12.37	.88	.27	13.61
1.90	8.72	11.05	2.40	12.38	12.42	2.90	16.44	13.66
.92	.86	11.11	.42	.54	12.48	.92	.62	13.70
.94	9.00	11.17	.44	.69	12.53	.94	.79	13.75
.96	.14	11.23	.46	.85	12.58	.96	.96	13.80
.98	.28	11.29	.48	13.00	12.68	.98	17.13	13.84

618. Examples of weir calculations. A weir 5 ft. long is set in a channel 10 ft. wide and the crest is 4.36 ft. high. If the observed head is

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0.64 ft., compute the discharge (*a*) by the Francis, (*b*) by the Fteley and Stearns, (*c*) by the Smith formula.

(*a*) Francis formula: $Q = 3.33\ (5 - 0.1 \times 2 \times 0.64)\ \sqrt{0.64^3} = 3.33 \times 4.872 \times 0.512 = 8.31$ cu. ft. per sec.; not corrected for velocity of approach V_A Area of channel of approach $A = (4.36 + 0.64)\ 10 = 50$ sq. ft. Velocity of approach $V_A = Q/A = 8.31/50 = 0.1662$ ft. per sec. Velocity head $h_v = (0.1662)^2/64.32 = 0.0004$; $\sqrt{H^3} = \sqrt{(0.64 + 0.0004)^3} - \sqrt{0.0004^3} = 0.5125 - 0.000008 = 0.5124$; $Q = 3.33 \times 4.872 \times 0.5124 = 8.313$ cu. ft. per sec.

(*b*) Fteley and Stearns formula: $Q = 3.31\ (5 - 0.1 \times 2 \times 0.64)\ \sqrt{0.64^3} + 0.007 \times 5 = 3.31 \times 4.872 \times 0.512 + 0.007 \times 5 = 8.29$ cu. ft. per sec.; h_v (as above) $= 0.0004$; $H = 0.64 + 2.05 \times 0.0004 = 0.6408$; $\sqrt{H^3} = 0.513$; $Q = 3.31 \times 4.872 \times 0.513 + 0.007 \times 5 = 8.31$ cu. ft. per sec.

(*c*) Hamilton Smith formula: $Q = 0.607 \times \frac{2}{3} \times 5 \times 8.02 \times \sqrt{0.64^3} = 8.308$ cu. ft. per sec.; h_v (as above) $= 0.004$; $H = 0.64 + 1.4 \times 0.0004 = 0.6406$; $\sqrt{H^3} = 0.5127$; $Q = 0.607 \times \frac{2}{3} \times 5 \times 8.02 \times 0.5127 = 8.320$ cu. ft. per sec.

In the foregoing solutions it is seen that the effect of velocity of approach is negligible, as is usually the case when the velocity is less than half a foot per second.

619. Further examples of weir calculations. Given a suppressed weir 7 ft. long, with crest 4.5 ft. above the bottom of the channel; the observed head is 1.36 ft. Compute the discharge by the Francis, Fteley and Stearns, and Bazin formulas: (*a*) not correcting for the velocity of approach; (*b*) correcting for the velocity of approach.

(*a*) Francis formula: $Q = 3.33 \times 7 \times \sqrt{1.36^3} = 36.97$ cu. ft. per sec. Fteley and Stearns formula: $Q = 3.31 \times 7 \times \sqrt{1.36^3} + 0.007 \times 7 = 36.80$ cu. ft. per sec.

(*b*) Francis formula: $A = 7 \times 5.86 = 41.02$ sq. ft.; $V_A = Q/A = 36.97/41.02 = 0.90$ ft. per sec; $h_v = (0.90)^2/64.32 = 0.0126$ ft.; $\sqrt{H^3} = \sqrt{(1.36 + 0.0126)^3} - \sqrt{0.0126^3} = 1.610$; $Q = 3.33 \times 7 \times 1.61 = 37.50$ cu. ft. per sec.

Fteley and Stearns formula: $V_A = 36.70/41.02 = 0.894$; $h_v = (0.894)^2/64.32 = 0.0124$; $H = 1.36 + 1.50 \times 0.0124 = 1.379$; $\sqrt{H^3} = 1.620$; $Q = 3.31 \times 7 \times 1.620 + 0.007 \times 7 = 37.58$ cu. ft. per sec.

Bazin formula: Bazin's coefficient (Par. **621**) includes effect of velocity of approach; $Q = 0.4266 \times 7 \times 1.36\ \sqrt{64.32 \times 1.36} = 37.97$ cu. ft. per sec.

620. Smith's weir coefficients. C_s = coefficient for weirs with the contraction suppressed at both ends and complete crest contraction.

Effective head in feet, H	Length of weir in feet				
	$L = 0.66$	2	3	4	5
0.1	0.675	.....	.....	.....	0.659
0.15	0.662	0.652	0.649	0.647	0.645
0.2	0.656	0.645	0.642	0.641	0.638
0.25	0.653	0.641	0.638	0.636	0.634
0.3	0.651	0.639	0.636	0.633	0.631
0.4	0.650	0.636	0.633	0.630	0.628
0.5	0.650	0.637	0.633	0.630	0.627
0.6	0.651	0.638	0.634	0.630	0.627
0.7	0.653	0.640	0.635	0.631	0.628
0.8	0.656	0.643	0.637	0.633	0.629
0.9	.....	0.645	0.639	0.635	0.631
1.0	.....	0.648	0.641	0.637	0.633
1.1	.....	.....	0.644	0.639	0.635
1.2	.....	.....	0.646	0.641	0.636
1.3	.....	.....	0.648	0.643	0.638
1.4	.....	.....	.....	0.644	0.640
1.5	.....	.....	.....	0.646	0.641
1.6	.....	.....	.....	0.647	0.642
1.7	.....	.....	.....	.....	.....

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C_e = coefficient for weirs with complete contraction at two ends and complete crest contraction.

Effective head in feet, H	Length of weir in feet						
	$L = 0.66$	1	2	2.6	3	4	5
0.1	0.632	0.639	0.646	0.650	0.652	0.653	0.653
0.15	0.619	0.625	0.634	0.637	0.638	0.639	0.640
0.2	0.611	0.618	0.626	0.629	0.630	0.631	0.631
0.25	0.605	0.612	0.621	0.623	0.624	0.625	0.626
0.3	0.601	0.608	0.616	0.618	0.619	0.621	0.621
0.4	0.595	0.601	0.609	0.612	0.613	0.614	0.615
0.5	0.590	0.596	0.605	0.607	0.608	0.610	0.611
0.6	0.587	0.593	0.601	0.604	0.605	0.607	0.608
0.7	0.585	0.590	0.598	0.601	0.603	0.604	0.606
0.8	.....	.....	0.595	0.598	0.600	0.602	0.604
0.9	.....	.....	0.592	0.596	0.598	0.600	0.603
1.0	.....	.....	0.590	0.593	0.595	0.598	0.601
1.1	.....	.....	0.587	0.591	0.593	0.596	0.599
1.2	.....	.....	0.585	0.589	0.591	0.594	0.597
1.3	.....	.....	0.582	0.586	9.589	0.592	0.596
1.4	.....	.....	0.580	0.584	0.587	0.590	0.594
1.5	.....	.....	.....	0.582	0.585	0.589	0.592
1.6	.....	.....	.....	0.580	0.582	0.587	0.591
1.7	.....	.....	.....	.....	.....	.....	.....

621. Bazin's coefficients. Values of m corresponding to heads (h) and heights of weir (p) in feet for use in Bazin's formula.

$$Q = mL\sqrt{2gh^3}$$

h (ft.)	$p=$ 0.656	$p=$ 1.0	$p=$ 1.5	$p=$ 2	$p=$ 2.5	$p=$ 3	$p=$ 4	$p=$ 5	$p=$ 6	$p=$ 6.56
0.2	0.456	0.449	0.446	0.444	0.444	0.443	0.443	0.443	0.443	0.443
0.3	0.457	0.446	0.440	0.438	0.436	0.436	0.435	0.435	0.434	0.434
0.4	0.463	0.448	0.439	0.435	0.433	0.432	0.431	0.430	0.430	0.430
0.5	0.469	0.451	0.440	0.435	0.432	0.430	0.428	0.427	0.427	0.427
0.6	0.476	0.455	0.442	0.435	0.431	0.429	0.427	0.425	0.425	0.424
0.7	0.482	0.460	0.444	0.436	0.432	0.429	0.426	0.424	0.423	0.423
0.8	0.489	0.465	0.447	0.438	0.433	0.430	0.426	0.424	0.423	0.422
0.9	0.495	0.470	0.451	0.440	0.434	0.430	0.426	0.424	0.422	0.422
1.0	0.501	0.475	0.454	0.443	0.436	0.432	0.426	0.424	0.422	0.421
1.1	.....	0.479	0.457	0.445	0.438	0.433	0.427	0.424	0.422	0.421
1.2	.....	0.483	0.461	0.448	0.439	0.434	0.428	0.424	0.422	0.421
1.3	.....	0.487	0.464	0.450	0.441	0.435	0.428	0.424	0.422	0.421
1.4	.....	0.491	0.467	0.452	0.443	0.437	0.429	0.425	0.422	0.421
1.5	.....	0.495	0.470	0.455	0.445	0.438	0.430	0.425	0.422	0.421
1.6	.....	.....	0.473	0.457	0.447	0.440	0.431	0.425	0.422	0.421
1.7	.....	.....	0.475	0.459	0.448	0.441	0.431	0.426	0.422	0.421
1.8	.....	.....	0.478	0.461	0.450	0.442	0.432	0.426	0.422	0.421
1.9	.....	.....	0.480	0.463	0.452	0.444	0.433	0.427	0.423	0.421
2.0	.....	.....	0.483	0.465	0.453	0.445	0.434	0.427	0.423	0.421

622. Other forms of weir notches have been proposed and used, the most common of which are of Cippoletti, a trapezoidal notch, and the **triangular notch** (Fig. 53). The object of the Cippoletti weirs was to eliminate the effect of the end contractions. According to experiments by Horton*

* Water Supply and Irrigation Paper No. 200 U. S. Geol. Survey; Washington, D. C.

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when the batter of the sides is 1 in 4 this aim is accomplished. The formula for any **trapezoidal weir** takes the usual form

$$Q = CL\sqrt{H^3} \qquad \text{(cu. ft. per sec.)} \qquad (110$$

in which C for the special form cited has been experimentally determined as 3.367. Correction for velocity of approach may be made as for the Francis weir. The advantage of this weir is that a constant length L may be used for all heads so that for continuous measurements with varying heads it saves much labor. This form has been much used in irrigation projects in the Western United States. By adding 1 per cent. to the value of Q found in the weir table in Par. **617** the discharge for this weir may be computed.

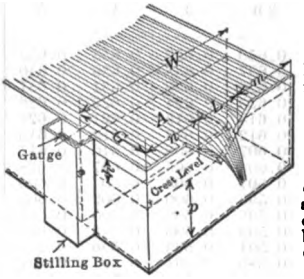


FIG. 53.—Triangular weir.

623. Triangular (notch) weirs. The common triangular notch is right angled set with the apex down and the bisector of this angle vertical (Fig. 53). It has been found by experiment that the coefficient of such a triangular weir is remarkably constant for all heads. The formula for a right-angled notch set as described reduces to

$$Q = C\sqrt{H^5} \qquad \text{(cu. ft. per sec.)} \qquad (111$$

in which C may be taken as 2.54 when H is measured to the apex of the angle. For measuring small quantities of water where the necessary head consumed is unimportant the V notch furnishes an accurate means and has been developed commercially as the **Lea Recorder.**

624. Flow of water in channels, whether open or closed, is subject to the same fundamental laws, and the formulas in common use are based on the two primary conceptions stated in Par. **602** and **603.** Head is required to produce velocity, to overcome obstructions such as bends, sudden constrictions or enlargements and head is required to overcome friction. Friction in turn depends on the velocity of flow and on the surface over which the water flows, its extent, and its character. In any formula for discharge the extent of the rubbing surface in contact with the water may be cared for directly by a numerical factor known as the **mean hydraulic radius,** which is found by dividing the cross-sectional area of the stream by its wetted perimeter; the latter is the linear dimension of that part of the boundary line of the cross section of a channel in contact with the water. The effect of the character of the surface must be cared for by empirical coefficients. Head may be provided by natural topographical conditions as in the slope of a river bed or created artificially as in the case of an elevated reservoir feeding into a pipe line. In the formulas most commonly in use the head appears in the slope of the **hydraulic grade line** which is the fall in feet, per foot of distance measured along the longitudinal axis. The hydraulic grade line is a line in the plane of the longitudinal axis of the stream and at all points distant from it an amount equal to the net effective head. In an open channel the hydraulic grade line is coincident with the surface of the water. In the case of a pipe or conduit flowing under pressure the hydraulic grade line is above the centre line of the pipe and distant from it as defined above.

625. The Chezy formula is probably the most satisfactory one to use certainly for open channels. It is usually stated as follows:

$$V = C\sqrt{RS} \qquad \text{(ft. per sec.)} \qquad (112$$

where C = coefficient increasing with the mean hydraulic radius, and for new clean channels usually increasing with the mean velocity of flow, and decreasing with the roughness of the channel; R = mean hydraulic radius, and S = sine of the slope of the hydraulic grade line. The common text-book formula which, as nearly as may be determined, was proposed by Weisbach.*

* Weisbach's "Mechanics" (Coxe's translation), page 866. This formula is not uncommonly designated as Weisbach's, Darcy's, Weston's, or Chezy's

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l which is used only for pipes under pressure, is as follows (for steady form flow under pressure in circular pipes):

$$h_f = f\left(\frac{LV^2}{2gD}\right) \qquad \text{(ft.)} \qquad (113)$$

ere h_f = the head lost in friction, f = the friction factor or coefficient of tion, decreasing with an increase in the diameter of the pipe and commonly h an increase of velocity of flow; and increasing with the age and roughness the surface in contact with the water (Par. **626**). L = the length (in ft.) he pipe measured on its axis; D = the internal diameter (in ft.) of the pipe; the mean velocity of flow in ft. per sec.; g = the acceleration due to vity, taken here as 32.16. The above equations are merely different ressions for the same formula. Either may be used to suit convenience. alues of C suggested for use in Eq. 112 are as follows: New cast-iron pipe l carefully without abrupt changes in grade or alignment: sizes 6 in. to in., velocities 3 to 8 ft. per sec., $C = 102$ to 108; sizes 12 in. to 20 in., velo- es 1 to 5 ft. per sec., $C = 105$ to 115; sizes 20 in. to 60 in., velocities 1 to 6 per sec., $C = 120$ to 150. Riveted steel pipe (new): sizes 16 in. to 102 in., ocities 2 to 5 ft. per sec., $C = 100$ to 115. Tunnel or aqueduct with oth cement or hard brick lining of relatively small cross-sectional areas to 50 sq. ft.): velocities 1 to 5 ft. per sec., $C = 115$ to 140. Small al, cross-sectional area about 100 sq. ft. in loose gravel or rock: velocities o 5 ft. per sec., $C = 60$ to 85. Large canal, wide and shallow, smooth tom and sides: velocities 2 to 5 ft. per sec., $C = 50$ to 70. Large canal, e and deep, fairly smooth bottom and sides: velocities 2.5 to 3.5 ft. per , $C = 75$ to 90. Large river, tortuous channel: $C = 40$ to 80. Large river, y bends: $C = 70$ to 100. Where the carrying capacity of any pipe or chan- is very important about 30 per cent. depreciation should be figured in rance.

626. Friction factors (f in Eq. 113, Par. **625**) for pipes may be computed Weston's formula.* This formula, which must only be applied to pipes ring interior sides similar to lead and brass pipes, from one-half inch to ee and one-half inches in diameter is as follows:

$$f = 0.0126 + \frac{0.0315 - 0.06d}{\sqrt{v}} \qquad (114)$$

which d = internal diameter of the pipe in feet; and v = the velocity in per second.

'or pipes with interior sides similar to new cast-iron pipes the following nulas are used:

$$f = \left(0.017379 + \frac{0.0015965}{d} + \frac{0.0040723 + \frac{0.000020816}{d^2}}{v}\right)\frac{l}{d}\,\frac{v^2}{2g} \qquad (115)$$

$$f = \left(0.0198920 + \frac{0.00166573}{d}\right)\frac{l}{d}\,\frac{v^2}{2g} \qquad (116)$$

e first formula (Eq. 115) is for velocities of flow less than 0.33 ft. per , the second for higher velocities.

627. The Kutter formula though intended and largely used for pipes as ll as for open channels, is not recommended for general use in either case.

$$V = \left[\frac{41.66 + \frac{1.811}{n} + \frac{0.00281}{S}}{1 + \left(41.66 + \frac{0.00281}{S}\right)\frac{n}{\sqrt{R}}}\right] \times \sqrt{RS} \qquad (117)$$

estimate directly a value of C (Par. **625**) is simpler, and probably quite as urate as to estimate a value of n. The value of n depends on the value S. Considering that in picking out the value of n a variation of 0.001 for all values of n and R may change the value of C as much as 17 per cent.,

* "Tables showing Loss of Head due to Friction of Water in Pipes" by mund B. Weston, C. E., D. Van Nostrand Co., 3rd Edition, 1903.

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and for moderate values as much as 5 to 8 per cent., it should be obvious that hair-splitting calculations with the Kutter formula are a needless waste of time, producing merely numerical accuracy instead of a high degree of precision. Though it seems evident that we shall never have one formula to fit accurately all kinds of channels, it appears probable that we may have a small group of formulas each of which will fit some particular class of channels.

Values of n to be used in the Kutter formula for calculating values of C to be used in the Chezy formula are as follows:

$n = 0.01$: should never be used except for temporary work and then only for perfectly smooth, clean iron pipes under 8 in. diameter and for high velocities, or for temporary and new planed wooden stave pipes, at high velocity 10 in. and under in diameter.

$n = 0.011$: for above pipes, and low velocity.

$n = 0.012$: for above pipes 3 ft. or more in diameter and high velocities; old iron pipes 8 in. diameter or under, low velocities; old city water mains above 8 in. diameter. Also for concrete tunnels having $R = 2.5$; wood flumes open, planed plank, long bends.

$n = 0.013$: for above pipes 36 in. to 120 in. diameter, old pipes and low velocities; 1-to-2 cement-lined pipes; new penstocks lined with unplaned lumber and running full at all times; large concrete-lined tunnels of area 100 to 200 sq. ft.

$n = 0.0135$: Ashlar masonry and well laid brickwork penstocks over 3 ft. in diameter; cast-iron concrete or steel-riveted pipes 8 in. to 20 in diameter, long in use, short joints and under pressure of 75 to 150 lb. per sq. in.

$n = 0.015$: rough concrete pipes where the interior cannot be smoothed or kept clean, moderate velocities and diameters above 3 ft.; penstocks of poorly laid rough brickwork; concrete-lined, open canals, low velocities.

$n = 0.017$: canals with gravel bottom and sides well rammed, stones being 0.3 to 0.7 in. diameter; tunnels through hard rock, well trimmed and roughly faced; very large open concrete-lined canals.

$n = 0.02$: rough rubble masonry; canals through rock, or with bottom and sides paved with cobble stones; canals in earth with bottoms and sides well trimmed; small rough lumber penstocks with battens and poor alignment.

$n = 0.0225$: canals in earth in good condition, but long in use, having moss growing freely.

$n = 0.025$: canals in clay, long in use; small rivers, deep and narrow and with no sharp bends, smooth sand bottoms and smooth uniform banks.

$n = 0.0275$: canals and rivers as for $n = 0.025$, but having an occasional bend and snag also the same, but with gravel bottoms; earth canals as left by dredging.

$n = 0.03$: rivers having loose boulder beds, irregular banks, sharp bends, shallow, normal flow.

$n = 0.035$: rivers with rough, irregular beds having shallows and pools, snags, bends, gravel bottoms, average flood stages.

$n = 0.05$: large shallow rivers, having sharp bends, low heavily wooded banks, snags, shallows, pools, rough bottom and moderate flood conditions.

$n = 0.055$: large torrential streams during high floods, with the banks heavily-wooded and inundated; mountain streams with many falls, large boulders, rapids, etc.

628. Beardsley's formula for C. Assuming values for n, S and R, C may be calculated from the formula as given by R. C. Beardsley.

$$C = \frac{\left(23 + \frac{1}{n} + \frac{0.00155}{S}\right)}{\left(0.5521 + \left[23 + \frac{0.00155}{S}\right]\frac{n}{\sqrt{R}}\right)} \qquad (118$$

or in its original form

$$C = \frac{\left(41.66 + \frac{1.811}{n} + \frac{0.00281}{S}\right)}{\left(1 + \left[41.66 + \frac{0.00281}{S}\right]\frac{n}{\sqrt{R}}\right)} \qquad (119$$

629. Bazin's formula for C. Bazin proposed a formula for computing the value of C to be used in the Chezy formula which differs from the Kutter

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formula in eliminating S and making the variation in C depend only upon variations in the mean hydraulic radius and the coefficient of roughness. It is as good as any general formula and has the advantage of simplicity. His formula is

$$C = \frac{157.6\, R^{\frac{1}{2}}}{R^{\frac{1}{2}} + \gamma} \qquad (120)$$

Values of γ

$\gamma = 0.109$: very smooth surfaces; neat cement; planed wood.
$\gamma = 0.290$: smooth surfaces; planks, bricks, ashlar.
$\gamma = 0.833$: rough surfaces; rubble masonry.
$\gamma = 1.54$: canals with mixed linings; very regular earth or paved with stones.
$\gamma = 2.35$: earth canals in ordinary conditions.
$\gamma = 3.17$: earth canals in bad condition.

Basin's formula represents the results of a very careful study of existing data and is extremely valuable in designing relatively small channels and those with very smooth linings; it also meets the conditions of design for all open channels as well as, if not better than any general formula available. It has the additional merit of simplicity.

630. Friction loss in iron pipes increases with age. Under ordinary conditions of service at the end of 30 years we may expect to find the losses in cast-iron pipes due to friction about doubled. This is satisfactory for rough approximations and the loss for intermediate years may be taken as proportional to the age.

631. Loss of head at entrance. The flow formulas which have been given (Par. **605** to **629**) take into account only the head necessary to overcome friction. There is in addition to this a further loss of head in creating

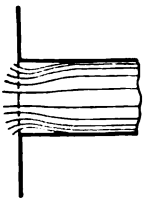


FIG. 54a.

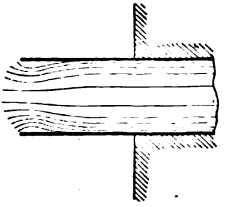


FIG. 54b.

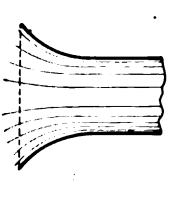


FIG. 54c.

the velocity of flow and in overcoming the resistance of entrance into the pipe. The **velocity head** is equal to $V^2/2g$. The head lost at entrance varies with the form of entrance and is expressed as a constant times the velocity head $\xi \cdot V^2/2g$. Values of ξ are given below.

$$0.5\frac{V^2}{2g} \qquad (0.11 \text{ to } 0.02)\frac{V^2}{2g} \qquad 0.93\frac{V^2}{2g}$$

632. Nozzles, properly designed, furnish one of the simplest and most accurate methods of measuring small quantities of water. Coefficients of discharge for various forms of nozzles from about $\frac{1}{4}$ in. to 5 in. have been determined with great accuracy by John R. Freeman.* Nozzles are especially useful in measuring the discharge through pipes, fire hose, and in testing the performance of pumps and impulse water wheels. With nozzles to which Freeman's coefficients are applicable, discharge measurements can be made with an error not exceeding 2 per cent.

633. Loss of head due to bends, elbows, valves, etc. Experimental data are either meager or lacking from which to compute the loss of head due to bends, elbows, valves, etc. Their effect only becomes important with high velocities and may be considered as corresponding to so many additional

* *Trans.* Am. Soc. C. E., Vol. XXI, pp. 303–462.

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feet of straight pipe. In long uniform pipe lines laid with easy curves the friction loss predominates and the minor losses may be neglected. The following table gives approximate values determined by experiments made by the Inspection Department of the Associated Factory Mutual Fire Insurance Companies, and may be used when no exact information is available:

Name of fitting	Number of feet of clean, straight pipe of same size which would cause the same loss as the fitting. (Loss in straight smooth pipe as given by Weston).
2.5-in. to 8-in. long-turn ells	4
2.5-in. to 8-in. short-turn ells	9
3-in. to 8-in. long-turn tees	9
3-in. to 8-in. short-turn tees	17
1/8th bend	5

634. Freeman's formula for nozzles is given as follows:

$$G = 29.83\ Cd^2\sqrt{\frac{P_e}{1-C^2\left(\frac{d}{D}\right)^4}} \quad \text{(gal. per min.)} \qquad (121)$$

where G = discharge in gallons per minute, C = coefficient of discharge, d = diameter in inches of the nozzle orifice, D = diameter in inches of the piezometer ring at the base of the nozzle, and P_e = piezometer reading in pounds

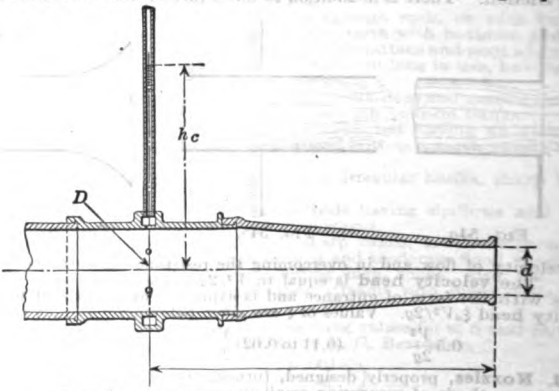


FIG. 55.—Section of nozzle and piezometer ring.

per square inch at the centre of the nozzle orifice. For water-power practice in engineering units the same formula becomes:

$$Q = 6.3Cd^2\sqrt{\frac{h_e}{1-C^2\left(\frac{d}{D}\right)^4}} \quad \text{(sec-ft.)} \qquad (122)$$

where Q = discharge in cubic feet per second, C = coefficient of discharge, d = diameter in feet of the nozzle orifice, D = diameter in feet of the piezometer ring at the base of the nozzle, and h_e = piezometer reading in feet of water above the center of the nozzle orifice.

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635. Coefficients for nozzles. A value of 0.974 may be taken as a suitable coefficient (C) for the ordinary smooth fire nozzle with a nominal diameter between 0.75 in. and 1.375 in. and under pressures varying from 20 to 100 lb. per sq. in. For pressures less than 20 lb. per sq. in. the same coefficient may be used, but without so great a confidence in the accuracy of the result. For larger sizes of smooth nozzles ranging from 1.75 in. and 2.5 in. Freeman's coefficients lie between 0.987 and 0.999 for pressures ranging from 15 to 55 lb. per sq. in. For smooth nozzles from 2.5 in. up to 6 in. and under heads of more than 10 ft., Freeman suggested a coefficient of 0.995. The following coefficients have been obtained by experiment for a set of specially made smooth meter nozzles (Fig. 56): 2.5 in., 0.98; 3 in., 0.985; 4 in., 0.99; 5 in., 0.995. The coefficients will vary somewhat in different sets of nozzles and it is important to know at what point the pressure is registered (Fig. 55). If special accuracy is desired a set of meter nozzles should be used. With nozzles the jet suffers contraction and the coefficients according to Freeman's experiments range from 0.65 up to 0.975 according to the proportions of the orifice.

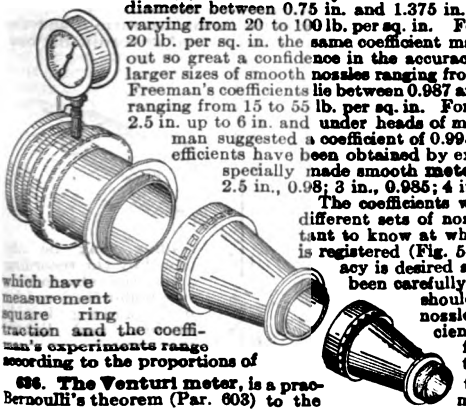


FIG. 56.—Meter nozzle.

636. The Venturi meter, is a practical application of Bernoulli's theorem (Par. 603) to the measurement of water in pipes flowing under pressure. The formula for discharge is

$$Q = \frac{C\pi D_b^2 D_a^2 \sqrt{2gh}}{4\sqrt{D_a^4 - D_b^4}} \quad \text{(sec-ft.)} \qquad (123)$$

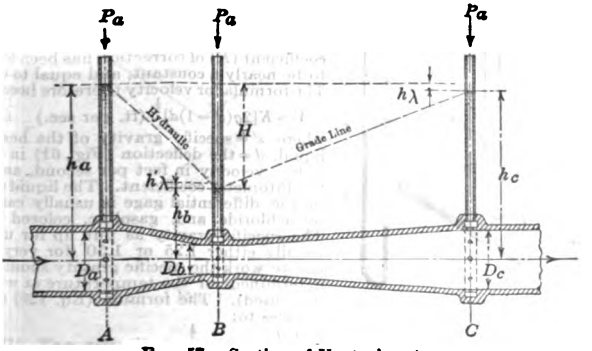


FIG. 57.—Section of Venturi meter.

The symbols will be understood by reference to Fig. 57. For meters with a given ratio of throat and inlet diameters the formula may be simplified. Let the ratio $R = D_a/D_b$ and let

$$K = \frac{\pi R^2}{4}\left(\frac{2g}{R^4 - 1}\right)^{\frac{1}{2}} \qquad (124)$$

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Then $Q = CKD_b^2\sqrt{H}$ (cu. ft. per sec.) (125)

Values of R	= 3.0	2.5	2.0
Values of K	= 6.338	6.381	6.505

The value of C varies wth the velocity at the throat, the ratio R and the actual dimensions of the meter. As the Venturi meters* are ordinarily constructed the coefficient C is between 0.97 and 1.03. These meters may be rated backward and a coefficient of correction found to apply to the manometer reading (Fig. 58). The total loss of head through the meter tube is relatively unimportant compared with other types of commercial meters and is so small that the insertion of the meter in the mains of a water supply is rarely objectionable, and the use of this appliance is growing constantly. It may be used particularly well in high-pressure power plants where a continuous reading may be obtained by the recording apparatus; also to measure boiler feed and for measuring liquids heavier and lighter than water. Experience has shown that with the register, continuous measurements have been made with an error not exceeding 3 per cent.

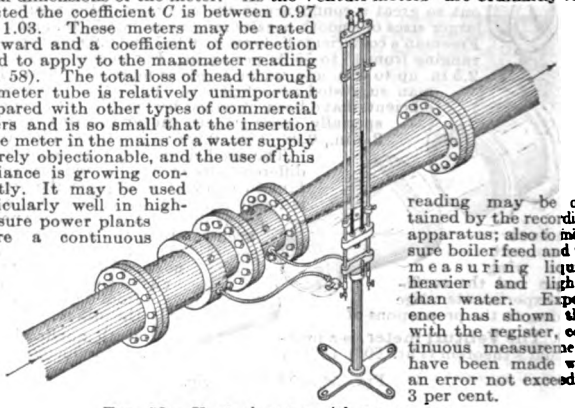


FIG. 58.—Venturi meter with manometer.

637. The Pitometer† (Figs. 59 and 60), by means of the differential gage registers the difference in pressure on the two orifices, one pointed directly against the current, the other in the exactly opposite direction. This difference in pressure is not a measure of the velocity head directly, but is greater than the velocity head. For these instruments the coefficient (K) of correction has been found to be nearly a constant, and equal to 0.84. The formula for velocity therefore becomes

$$V = K[2g(s'-1)d]^{\frac{1}{2}} \text{ (ft. per sec.)} \quad (126$$

where s' = specific gravity of the heavier liquid, d = the deflection (Fig. 61) in feet, V the velocity in feet per second, and K the Pitometer coefficient. The liquid used in the differential gage is usually carbon tetrachloride and, gasoline, colored red. The specific gravity as put up for use is usually either 1.25 or 1.50 (for very accurate work the specific gravity should be determined for the temperature at which it is used). The formula (Eq. 126) then reduces to:

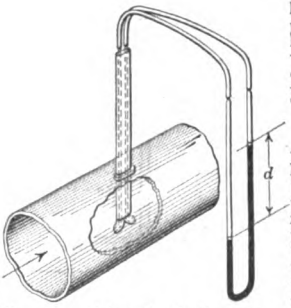


FIG. 59.—Principle of pitometer.

$$\text{For } s' = 1.25;\ V = 0.84\frac{\sqrt{2gd}}{\sqrt{4}} = 3.368d^{\frac{1}{2}} \text{ (ft. per sec.)} \quad (127$$

$$\text{For } s' = 1.50;\ V = 0.84\frac{\sqrt{2gd}}{\sqrt{2}} = 5.671d^{\frac{1}{2}} \text{ (ft. per sec.)} \quad (128$$

* Made by the Builders Iron Foundry, Providence, R. I., in standard sizes for pipe lines from 2 to 60 in. in diameter, and much larger sizes are in use; they may be furnished with either direct reading or recording apparatus.

† Developed by John A. Cole and Edward S. Cole and owned by the Pitometer Co., N. Y.

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To determine the discharge the cross-section of the pipe must be divided into one or more known areas (Fig. 61), the velocity for each found and hence the mean velocity for the entire cross-section; the discharge being simply the product of the area and the mean velocity. For pipes the following table (Par. **639**) is useful and the example (Par. **641**) illustrates how the discharge is calculated. The Pitometer is set so that the velocity is determined for the points as shown in Fig. 61. The pipe coefficient (see example) being first determined, it is subsequently necessary only to get a reading for the centre of the pipe and apply the coefficient to the centre velocity to obtain the mean velocity and hence the discharge by the formula:

$$Q = KCV_cA \qquad \text{(cu. ft. per sec.)} \qquad (129)$$

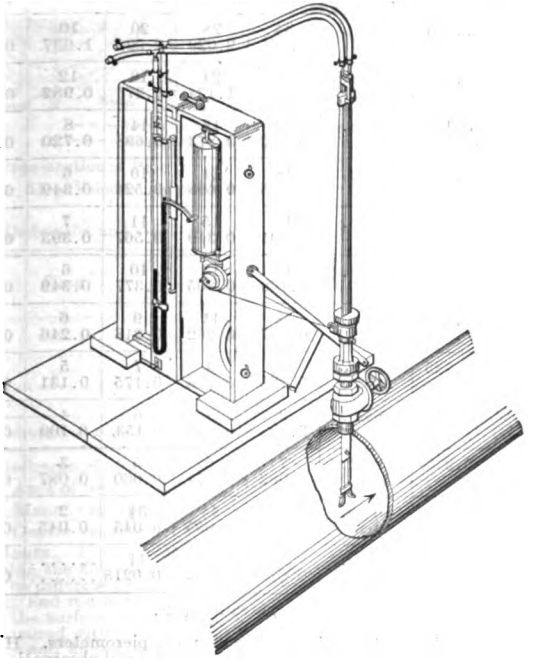


FIG. 60.—Portable pitometer.

638. The principal use of the pitometer is for measuring the flow in water mains where it has proved its great value in detecting leaks and waste, and in measuring the slip of pumping engines. It can be installed and operated for relatively small expense, without interfering with the flow. For large penstocks and in silt-bearing water it is not recommended. When used in old pipes, allowance must be made for incrustations reducing the cross-sectional area and a traverse of several points through more than one diameter is preferable to the single observation and the use of the pipe coefficient.

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639. Traverse table for pitometer gagings, showing inner diameter of each ring for ordinary sizes of mains in inches; and giving the area of each ring and centre circle in square feet.

Diameter of pipe (in.)	Area of pipe (sq. ft.)		Ring A	Ring B	Ring C	Ring D	Centre circle E
48	12.566	Diam.	44	36	28	16	16
		Area	2.007	3.490	2.793	2.880	1.396
42	9.621	Diam.	38	32	24	14	14
		Area	1.745	2.291	2.443	2.073	1.069
36	7.069	Diam.	34	28	20	10	10
		Area	0.764	2.029	2.094	1.637	0.545
30	4.909	Diam.	28	24	18	12	12
		Area	0.633	1.134	1.375	0.982	0.785
24	3.142	Diam.	22	18	14	8	8
		Area	0.502	0.873	0.698	0.720	0.349
20	2.182	Diam.	18	14	10	6	6
		Area	0.415	0.698	0.524	0.349	0.196
18	1.767	Diam.	17	15	11	7	7
		Area	0.191	0.349	0.567	0.393	0.267
16	1.396	Diam.	15	13	10	6	6
		Area	0.169	0.305	0.377	0.349	0.196
14	1.069	Diam.	13	11	9	6	6
		Area	0.147	0.262	0.218	0.246	0.196
12	0.785	Diam.	11	9	7	5	5
		Area	0.125	0.218	0.175	0.131	0.136
10	0.545	Diam.	9	8	6	4	4
		Area	0.103	0.093	0.153	0.109	0.087
8	0.349	Diam.	7	6	5	3	3
		Area	0.082	0.071	0.060	0.087	0.049
6	0.196	Diam.	5½	4½	3½	2	2
		Area	0.031	0.055	0.043	0.045	0.022
4	0.0873	Diam.	3½	2½	1½	.....	1½
		Area	0.0205	0.0327	0.0218	.....	0.0123

NOTE.—Diameter given in inches; area in sq. ft.

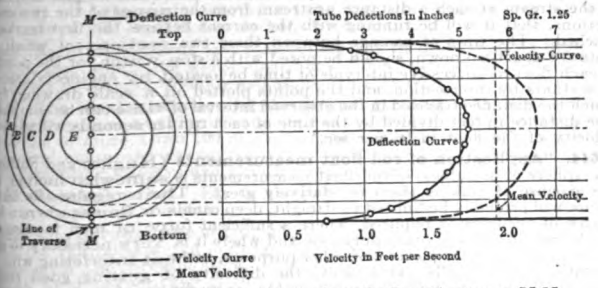
640. Piezometers. "Mills' experiments upon piezometers. Hiram F. Mills* published in 1878 the results of some six thousand observations made with extraordinary accuracy to determine the proper form of piezometer orifice. With twenty-two openings varied in shape and direction and a range of velocities from 0.6 to 8.9 ft. per sec., he found that with an orifice whose edges are in the plane of the side of the channel and passage normal thereto, the piezometer column will stand neither above nor below the surface of the stream, but will indicate the true height of the water surface in an open channel or the pressure in a closed channel; but if the passage inclines either upstream or downstream, or the edges of the orifice project

* Chief Engr. Essex Co., Lawrence, Mass. *Trans.* Am. Academy of Science, 1878.

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beyond the plane of the side, the true height of the surface or the true pressure will not be indicated."*

641. Example of use of pitometer. The following diagram (Fig. 61) and computations illustrate the usual method of computing discharge.



Cross-section of Pipe Longitudinal Section on M-M.

FIG. 61.—Velocity curve as determined by pitometer readings.

Deflection and velocity curves from 24-in. supply main

Ring	Ring areas (sq. ft.)	Ring velocity (ft. per sec.)	Ring volumes of flow (cu. ft. per sec.)
A	0.502	1.57	0.788
B	0.873	1.87	1.632
C	0.698	2.05	1.431
D	0.720	2.18	1.570
E	0.349	2.24	0.781
Total discharge of pipe	3.142		6.202

$$\frac{\text{Discharge of pipe}}{\text{Area of pipe}} = \frac{6.202}{3.142} = 1.97 \text{ ft. per sec., mean velocity.}$$

$$\frac{\text{Mean velocity}}{\text{Centre velocity}} = \frac{V}{V_c}\frac{1.97}{2.24} = 0.879 = \text{pipe coefficient.}$$

642. Floats. Under favorable circumstances one of the simplest methods of measuring the flow of water is by means of velocity determinations with floats. The different kinds of floats are surface, subsurface, or combinations of the two, and rod floats. **Surface floats**, even on a perfectly quiet day, give only the surface velocity and with any wind blowing the velocity cannot be measured with accuracy. **Subsurface floats** are but slightly heavier than water and are easily caught by eddies and cross currents which move them about in an undeterminable path and make the results unreliable. **Twin floats** have been used, but their place is better filled by rod floats.

643. Rod floats are cylinders usually made of metal tubing loaded with lead at the bottom so that they will float vertically with about 6 in. extending above the surface of the water. They are best adapted for use in power canals with straight, smooth sides and level bottom so that rods may be used reaching nearly to the bottom without danger of bumping. Under such conditions rod floats have been used continuously on a large scale for a great many years. The method of measurement is direct. The

* Hughes & Safford, "Hydraulics;" New York, MacMillan Co., 1911, page 104.

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following paragraphs are quoted from Hughes and Safford's Hydraulic (MacMillan Company):

"Procedure in measuring velocity. A straight stretch of stream should be selected as a place for gaging, and two cross-sections selected to mar the beginning and the end of the area. The float should be placed quietl in the stream at such a distance upstream from the upper of the two cros sections, that it will be running with the current before the first marker reached. The time of passage between these two sections, of which th distance apart is known, should be noted with a stop watch; or the positic of each float at successive intervals of time be located by engineers' transi or sextants by intersection, and the points plotted on a scale drawing, fro which the distance traveled in the observed interval of time can be computed The distance in feet divided by the time of each run in seconds will give th velocity of the float in ft. per sec."

644. "Application of rod float measurements (Hughes and Safford The sphere of usefulness of rod-float measurements is somewhat limited, an the expense of making them is relatively great. Their regular use in th future will probably be limited to straight, deep canals or flumes where a hig degree of accuracy is required, where a sufficient force of men is regularl employed for this and other purposes, and where it is very necessary to ga all the water used for power and other purposes, without interfering with th operation of the mills. Ordinarily, the difficulty of getting good resul from the sum of individual measurements, or readings of water wheels, due to the fact that the total discharge, which is simply the sum of the i dividual water wheels, often does not include the leakage or the water use for manufacturing purposes other than power; but the flume measuremen of the total quantity passing to each mill will cover everything. There is ver little opportunity to make such measurements in rivers or canals which do no have a regular cross-section; and for such conditions there is no question tha measurements by current meter (Par. **662** to **665**) will take the place of thos formerly made by rod floats. The most notable published gagings by ro floats are those by Humphreys and Abbott of the Mississippi River, thos described by James B. Francis in the Lowell Hydraulic Experiments, Dar and Bazin's gagings, and the gagings of certain rivers in India."

645. "Limits of accuracy in use of rod floats (Hughes and Safford With a straight, smooth flume of great depth, and velocities ranging fro 2 to 5 ft. per sec., quantities of water from a few hundred to 4,000 cu. ft. p sec. have been repeatedly measured with a probable error of 1 to 2 per cen This form of measurement, which in its successive steps gives the product the cross-section and the velocity of the water as indicated by the rod float is a perfectly natural one; and its simplicity appeals to the non-technic man." Rod floats cannot be run with the lower end closer than 2 or more i from the bottom. Some correction must be made to account for this slow layer of water which does not act on the float. The following formula w derived by J. B. Francis by comparing rod float measurements with a wei

$$C = 1 - 0.116\,(\sqrt{D} - 0.1) \qquad (13$$

where C = a coefficient of correction which multiplied by the observed velo ity will give the corrected velocity, and D = difference between depth of wat in flume and length of immersed part of tube, divided by depth of water.

Values of the Coefficient C

D	0	1	2	3	4	5	6	7	8	9
0.0	.....	1.000	0.995	0.992	0.988	0.986	0.983	0.981	0.979	0.97
0.1	0.975	0.973	0.971	0.970	0.968	0.967	0.965	0.964	0.962	0.96
0.2	0.960	0.958	0.957	0.956	0.955	0.954	0.952	0.951	0.950	0.94
0.3	0.948	.....	.....	.....	.....	.....	.....	.....	.....	.....

Direct interpolation may be made for intermediate values.

STREAM FLOW

646. Flow. Water power is derived from the pressure or force exert by water in falling through a given head. Its amount is determined b the equation

$$\text{H.P.} = [Q \times H \times E] \div 8.8 \qquad (130$$

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where H.P. is the horse power, Q is the flow of water in cubic feet per second, H is the head in feet, and E is the efficiency of the water-wheel.

647. Run-off is the result of rain falling on the contributing drainage area and represents that proportion of the rainfall that does not pass off as evaporation or through underground channels, the requirements for vegetation, etc., being included in the broader definition of evaporation.

648. Rainfall records have been obtained by the U. S. Weather Bureau at stations geographically widely distributed for a long period of time. The results are published monthly and annually in the reports of the Bureau.

649. The local variation in the annual rainfall in the United States is all the way from nothing in some years in the desert regions, to an occasional maximum of more than 100 in. in the mountains of the extreme northwest. In general mountain ranges receive a greater amount of precipitation than the surrounding valleys and yield a greater proportionate run-off.

650. Rainfall map. Fig. 62 shows a map of the United States giving the distribution of rainfall.

651. The percentage of run-off, by which is meant the ratio of the run-off to the rainfall on the drainage basin, varies greatly and in general increases with the precipitation. For this reason it is dangerous to figure on any fixed percentage of run-off. See Par. **655.**

652. The monthly run-off depends on the precipitation, climate, storage, character of the drainage basin, etc., and varies within wide limits. In New England the month of maximum run-off usually shows a flow from three to four times that of the mean for the year, while the minimum month frequently drops to one-tenth or less of the mean, and this is notwithstanding a comparatively uniform distribution of rainfall throughout the year.

653. The daily run-off shows still wider variation than the monthly, although the monthly figures are frequently used in preliminary estimates. This use of the monthly flows averages days of high and low flows thus giving a moderate mean. An actual power output cannot be obtained equal to estimates based on monthly flows unless very large pondage is available.

654. By Pondage is meant the storage created at a power development and used for taking care of the variations in the draft. *"It is the retention for one or more days of the flow of a stream during hours of light load, for use during hours of heavy load." This is of the greatest importance for developments with a varying or non-continuous load. For example, a mill on a 48-hour week basis operates only 28.6 per cent. of the time, and hence can use only that proportion of the flow, assuming an unregulated flow and no pondage; while sufficient pondage to equalise the flow during the week would increase the low water output nearly four-fold. Every reservoir and mill pond on any stream must be operated subject to the legal rights of others on the stream. The study of pondage and its proper handling is complicated in the general case, but as a rule comparatively simple of solution for any actual power plant. The reason is that it is involved with the load curve, the natural and legal restrictions of the flowage permissible, and flow detained, and the variation in head economically advisable. Granting the possibility and rights of pondage, the problem reduces to a consideration of fitting the use of water to the demands for power made on the station. If the station carries a typical combined power and lighting load, pondage is essential to satisfactory operation since the great demand for power is during the day-time and the early evening hours. If the head may be drawn down during the day so that the pond will be just filled up by the night flow, the most that is possible is being obtained from the river. In some cases of low-head and medium-head developments the advisable reduction in head is the controlling or limiting factor. As the head falls the power and efficiency of the water wheels fall if the speed is kept up, as it must be in hydro-electric stations. Foresight and study of the probable range of head variation make it possible to have wheels designed with characteristic curves specially suited to the case and a greater variation of head may be permitted.

*Progress report of Committee on Run-off of Boston Society of Civil Engineers, November, 1918.

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655. Stream flow data.

Name of river and gaging station	Drainage area sq. mi.	Years of record	Mean yearly run-off, sec. ft. per sq. mi.	Min. monthly flow, sec. ft. per sq. mi.	Max. flow, sec. ft.
Androscoggin River at Rumford Falls, Maine	2090	1892–1912	1.63	0.35	55,200
Merrimack River at Lawrence, Mass.	4452*	1880–1914	1.48	0.26	82,150
South Branch Nashua River at Clinton, Mass.	108.84*	1897–1916	1.67		
Connecticut River at Orford, N. H.	3100	1900–1916	1.73	0.093**	57,300
Hudson River at Mechanicsville, N. Y.	4500	1898–1917(*a*)	1.64		120,000
Susquehanna River at Conklin, N. Y.	2350	1913–1917	1.59		
Genesee River near Rochester, N. Y.	2360	1906–1917	1.08		48,300
Potomac River at Pt. of Rocks, Md.	9650	1902–1916	1.03	0.056**	219,000
Delaware River at Riegelsville, N. J.	6430	1907–1916	1.70	0.183**	144,000
James River at Cartersville, Va.	6230	1901–1916(*b*)	1.26	0.128**	106,000
Roanoke River at Old Gaston, N. C.	8350	1912–1916	1.02	0.095**	210,000
Chattahoochee River at West Point, Ga.	3300	1901–1916(*c*)	1.81		88,600
Coosa River at Riverside, Ala.	7060	1901–1916	1.68	0.173**	
Alleghany River at Red House, N. Y.	1640	1906–1916	1.83		40,000
Tennessee River at Florence, Ala.	30800	1895–1916	1.65	0.248(*f*)	499,000
Holston River near Rogersville, Tenn.	3060	1907–1916	1.40	0.160(*g*)	67,000
Mississippi River at St. Paul, Minn.	35700	1900–1916	0.315		80,800
Minnesota River near Mankato, Minn.	14600	1910–1916	0.155		43,800
Cedar River at Cedar Rapids, Iowa	6640	1906–1916	0.543	0.062(*e*)	54,000
Clearwater River at Kamiah, Idaho	4850	1911–1916	1.79	0.196**	76,600
Columbia River at The Dalles, Oregon	237,000	1879–1910	0.895	0.217	1,160,000
Tuolomne River near La Grange, Cal., incl. Turlock and Modesto Canals	1500	1901–1916(*d*)	2.15		
Pit River near Ydalpom, Cal.	5260	1911–1916	0.903		47,000
Feather River at Oroville, Cal.	3640	1902–1916	2.22	0.217**	187,000

*Net Drainage Area
**Min. Daily Flow.
(*a*) Omitting 1904 and 1905.
(*d*) Omitting 1913.
(*e*) Minimum daily during open water conditions.
(*f*) Minimum daily in 1878.

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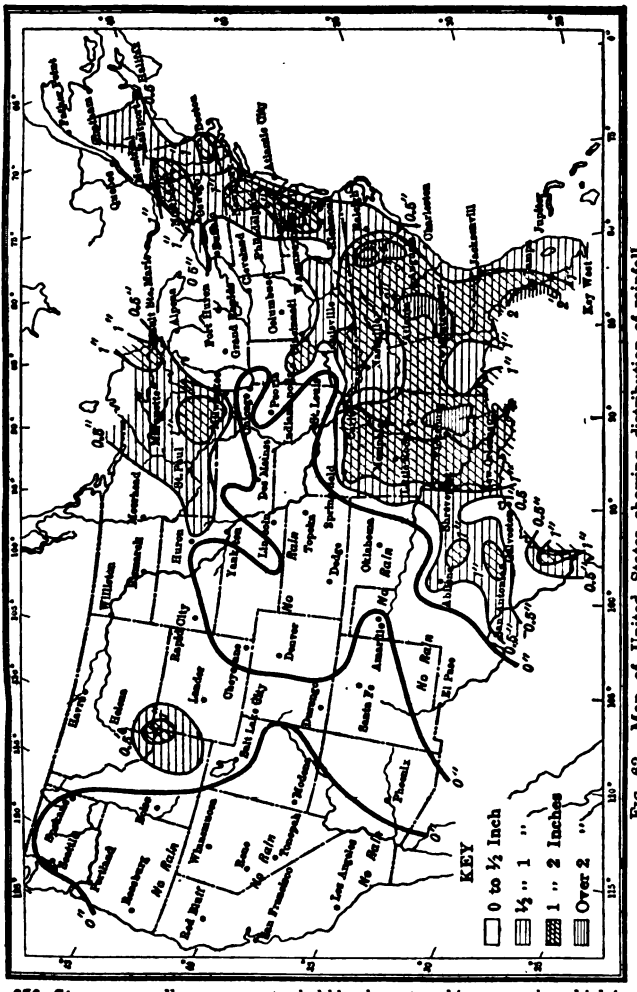


Fig. 62.—Map of United States showing distribution of rainfall.

656. Storage usually means water held back or stored in reservoirs which is available to increase the extremely low flows for several days, weeks or months. The development of storage on a drainage area is of the greatest importance, for otherwise the minimum flows reach a very low point and power must be obtained from other sources during the period of low flow.

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Storage reservoirs can be operated in two different ways:

(*a*) To produce a maximum amount of primary power, *i.e.*, power availab at all times. If operated in this way, reservoirs must be kept filled a lar part of the time in order to have the water available for use during exceptio ally dry periods.

(*b*) To use the stored water each year, or oftener if possible. In th case the reservoirs may be empty if a dry period is prolonged exceptionall A compromise between the two methods is usually best.

In any particular case the yield of a reservoir may be predicted from a stu of the run-off of the contributing area, the precipitation on and the evap ration from the water surface. Trial drafts from the storage are assumed a the effect traced through a number of years. In this way very safe estimat can be made of the storage yield.

657. Example of a large storage basin. The following figures show b way of illustration the condition of Lake Winnipiseogee (Par. **656**) on May Aug. 1, Nov. 1, and Feb. 1, using 1911 and 1912 figures of run-off and preci tation, and average figures of evaporation. The yield of the contributi area is expressed in inches of depth on the lake area, rainfall and evaporati are given directly in inches and the draft, 600 cu. ft. per sec. throughout t year, is also reduced to in. of depth on the lake area for each month.

Date	Yield of the contributing area expressed in in. of depth on the lake area for the month	Rainfall in in. during the month	Evaporation in in. during the month	Draft 600 cu. ft. per sec. expressed in in. of depth on the lake area for the month	Net gain or loss in in. of depth on the lake area for the month	Elevation of the lake*
April 1, 1911						27.5
During April	+38.35	+1.38	−1.6	−9.56	+28.57	
May 1, 1911						Wastir
July 1, 1911						38.0
During July	+ 1.83	+4.36	−4.32	−9.88	− 8.01	
August 1, 1911						30.0
October 1, 1911						15.4
During October	+ 9.44	+4.51	−2.20	−9.88	+ 1.87	
November 1, 1911						17.3
January 1, 1912						17.2
During January	+11.51	+3.12	−0.70	−9.88	+ 4.05	
February 1, 1912						21.2

* 44 in. represents full lake.

658. River gaging stations are maintained by the U. S. Government a the State Governments on many rivers and streams throughout the countr This work of gaging the rivers is carried on by the U. S. Geological Surve Dept. of the Interior, and the observations and results are published. The publications, which are invaluable in studying the possible water-pow development of our streams, may be obtained at nominal expense from t Supt. of Documents, Government Printing Office, Washington, D. C.

659. Flow in open streams is subject to the same laws as the flow any other channel (Par. **602**), but because of the irregularity of section a the changing character of the bed from point to point the difficulties of findi a formula to fit all conditions are manifold. The only reliable data concerni discharge of a stream are based on actual measurements.

660. Measurement of stream flow. The method adopted will depe largely on the size of the stream, its cross-section and the variation betwe minimum and maximum flow. A weir can be successfully used in a sm stream discharging a few cu. ft. per sec. and is largely employed

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rigation ditches. For rivers from medium to large size the most adaptable ethod is to employ a current meter and by making measurements at several tages of flow establish a **rating curve** by means of which it is only necessary o read a gage, compare the reading with the rating curve and find the ischarge corresponding to the given stage. The same rating curve cannot e used for both winter and summer conditions.

661. Typical hydrographs showing the monthly average stream flow in sec-ft. per square mile of drainage area are shown in Figs. 63 and 66, for he Kansas (Kan.) and Columbia (Ore.) rivers respectively. Figs. 64 and 67 how the accompanying monthly rainfall in typical years. Figs. 65 and 68 how the accompanying monthly evaporation. These stream-flow records r hydrographs naturally exhibit different characteristics according to the ocal climatic and other conditions, as noted by comparing Fig. 63 with Fig. 6, and Fig. 64 with Fig. 67. Furthermore, the hydrographs of the same river ary materially as a rule from year to year, between rather wide limits; Figs. 3 and 66, besides showing the stream flow for typical years, also show the aximum (wet year) and minimum (dry year) flow observed during a series f years. It is also instructive to compare the records of rainfall with those f stream flow; compare Figs. 63 and 64, and Figs. 66 and 67. Similar records nd charts should be obtained for any particular river or stream, if possible, n connection with consideration of its water-power possibilities.

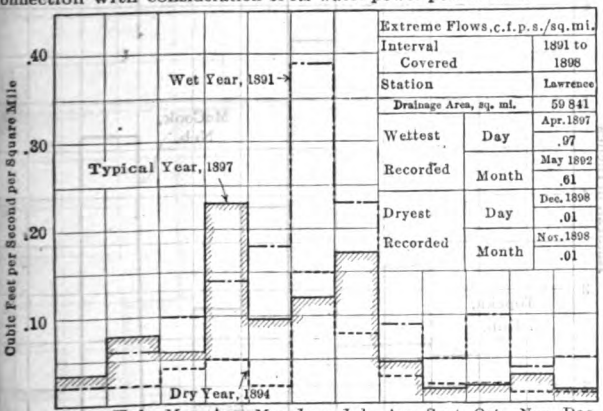


Fig. 63.—Hydrograph of Kansas River from records at Lawrence, Kansas.

662. Current meters may be roughly divided into two classes, those in hich the wheel revolves about a vertical axis and those in which the axis s horizontal.

The Price-Gurley meter (Fig. 69) belongs to the first class and is the type dopted by the government in its stream gaging work. It is fitted with a ane to keep it headed into the current and with an electric sounder to enable he operator to record the revolutions without taking the meter from the ater. This meter can be slung from a cable and operated from the shore or rom a bridge, or from a car suspended from a cable. In shallow water the eter is attached to a rod and operated directly by hand. The disadvantage herent in this meter is that it always records the maximum velocity, hether that velocity is in a forward direction or is merely caused by cross urrents and eddies; all alike are recorded as forward. Consequently this eter has a tendency to give results which are too high.

The Haskell meter (Fig. 70) is of the screw-propeller type and operated a the same manner as the Price-Gurley meter. It is subject to the same riticism in that it records the maximum velocity at the point of immersion egardless of its direction.

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The Fteley-Stearns meter (Fig. 71) was designed for use in the Sudbur Aqueduct of the Boston Water Works and is especially adapted for use i flumes or any channels where it is desired to get the velocity close to th sides and bottom. It is ordinarily fitted for use on a rod and is equippe with recording dials thrown in and out of mesh by a cord. The meter ca also be fitted up with vane and electric sounder. It then loses its peculi value in recording only the forward component of the velocity of the wate which makes it a true integrating instrument. It has been successfull used in large rivers and in velocities from 0.4 to 10 ft. per sec.

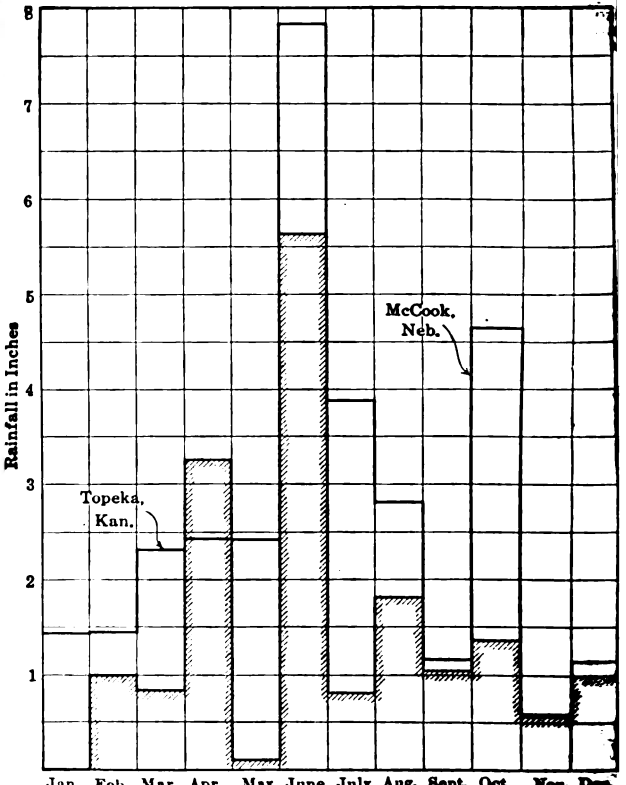


FIG. 64.—Monthly rainfall in Kansas River valley, 1897.

663. Water wheels as current meters. Water wheels if rated to dete mine their discharge with given head, gate opening, and speed, are in comm use as water meters in power plants. If occasionally checked by rod flo or current meter measurements they are quite accurate enough to base t use or sale of water on the quantities so determined. The Holyoke te (Par. **706**) of a wheel gives the necessary information from which a dischar

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ating curve may be constructed, but it is more satisfactory if in addition to this, careful measurements are made with the wheels in place.

664. Methods of using current meters are as follows:

(*a*) Single point at 0.6 depth.
(*b*) Two points at 0.2 and 0.8 the depth.
(*c*) Multiple point.
(*d*) Integrating: (1) vertically; (2) diagonally.

The single point method at 0.6 depth (*a*) is supposed to give the average velocity of the vertical section in which it is held. Except in special cases such as natural streams uncontrolled by local conditions this can rarely be relied upon.

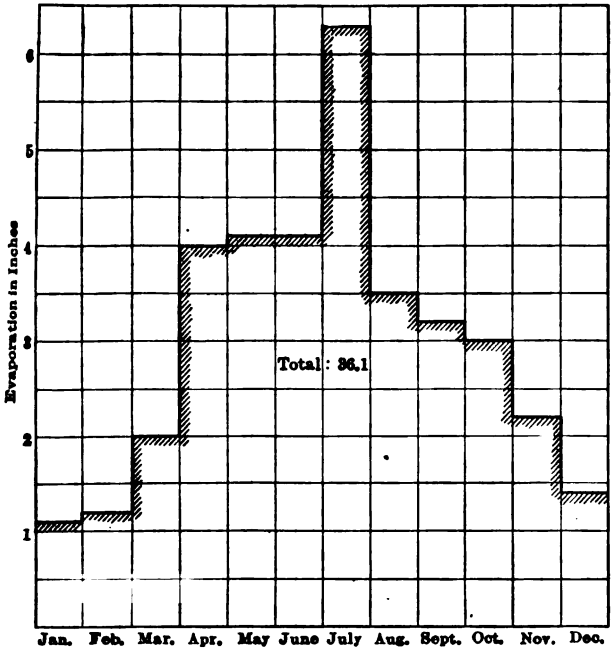


FIG. 65.—Monthly evaporation of Topeka, Kan., July, 1887–June, 1888, computed under the direction of T. Russell, U. S. Mo. Weather Review, Sept., 1888.

The average of the two velocities at 0.2 and 0.8 depth (*b*) is supposed to give the mean velocity of the vertical section in which it is held. The same comment applies.

These two methods have been advocated by the government service for quick measurements but are not recommended for accurate work, without actual determinations of velocity distribution in the stream cross-section.

By dividing the cross-section into several imaginary vertical strips of width depending on the total width of the stream and the uniformity of flow, and measuring the velocity at several points in each vertical strip the true mean velocity can be closely approximated. This method (*c*) is recommended for use in power canals where the flow is fairly steady so that during the ti-

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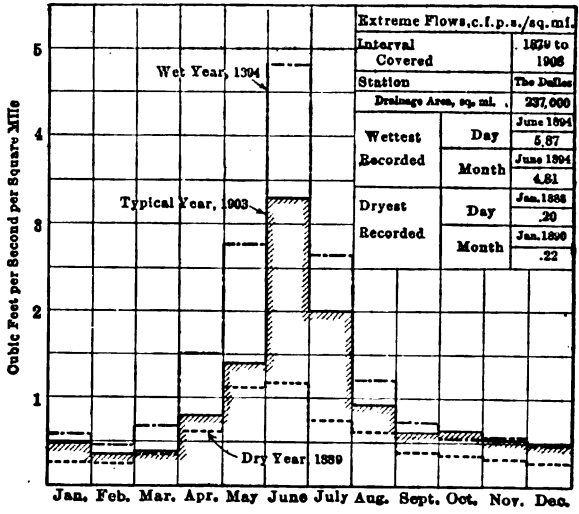


FIG. 66.—Hydrograph of Columbia River from records of The Dalles, Oregon.

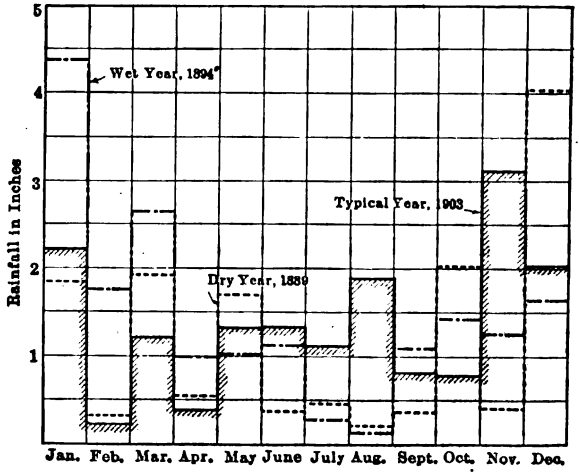


FIG. 67.—Monthly rainfall at Spokane, Wash.

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consumed in making the measurement there is no material change. It is especially useful in showing the distribution of the velocity over the cross-section.

Vertical integrating measurements (*d*) (1) are made by slowly lowering the meter from top to bottom and raising it again along the same vertical path. In this way the average velocity for the strips in order is obtained mechanically. Diagonal integration (*d*) (2) the meter is moved slowly across the stream at the same time it is being lowered and raised. By this method the mean velocity for the entire cross-section of the stream is obtained in one continuous operation.

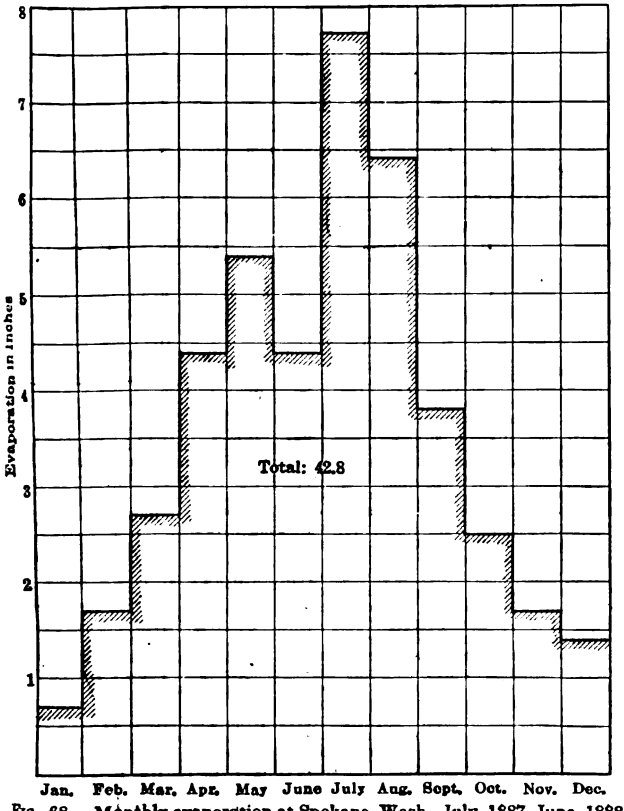


FIG. 68.—Monthly evaporation at Spokane, Wash., July, 1887–June, 1888, computed under the direction of T. Russell, U. S. Mo. Weather Review, Sept., 1888.

665. Choice of method. The width of the channel, the conditions of flow and the degree of accuracy desired are important considerations in

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selecting the method to be used. By dividing the stream cross-section b verticals into areas of equal width, through the centre line of which the met is lowered and raised with uniform speed, the mean velocity in ft. per se

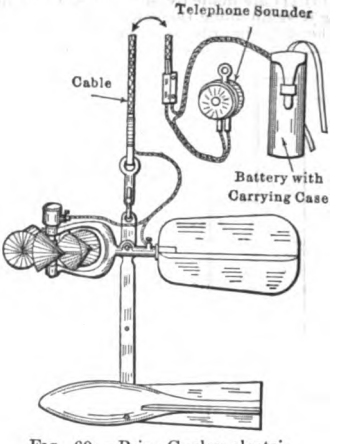


FIG. 69.—Price-Gurley electric current meter.

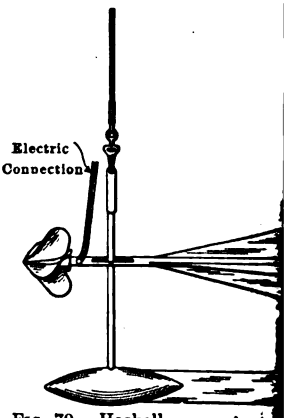


FIG. 70.—Haskell current me

for each section is obtained in one operation. This method is on the whol be preferred for determinations of discharge. The multiple-point metho of great value in determining the distribution of velocity in any cross-secti which is often necessary for at least one gaging; but for determination of discharge this method is tedious and if the stream is subject to fluctuation in stage it is too slow.

If the channel is not too wide or deep the diagonal integration which covers the whole stream in one operation is a very satisfactory form of measurement because it permits a great many measurements under different conditions and avoids many disturbing conditions. Its use is limited by the endurance of the operator. The double-point and single-point methods are only rough approximations, but serve a useful purpose in securing information of stream flow at low cost.

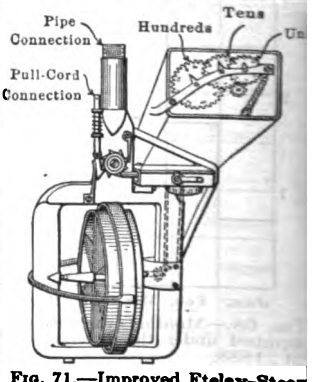


FIG. 71.—Improved Fteley-Stear current meter.

666. Effect of ice. Ice cover on a stream or canal decreases the cross-section, and increases the wetted perimeter or rubbing surface. Both of these result in additional loss of head, the first through increasing the velocity, the second through increasing the frictional resistance to flow. In power canals the formation of an ice cov of sufficient thickness to last through the cold season is a protection again troubles from anchor ice and frazil ice. Neither anchor ice nor frazil i will form under an already existing ice cover; the latter is therefore desirab

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l canals should be designed with this in mind, and the velocities should be ɔt down (2 to 3 ft. per sec.) by making the cross-section ample for ex- me conditions. Anchor ice is ice which forms on the bottom of the stream canal and may seriously obstruct the flow. Frasil or needle ice forms, as name implies, in small needles where the current is too rapid for the mation of surface ice. It may either attach itself to the bottom or to :hor ice already formed or it may be carried against and effectually clog racks of a power house.

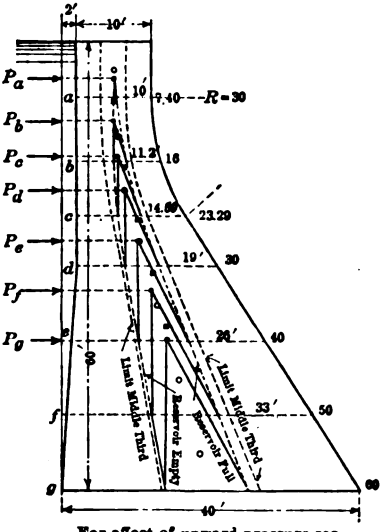
DAMS AND HEADWORKS

667. **Dams**, regardless of the material composing them, may be roughly ssified into two main divisions: (*a*) Impounding dams for holding water k, as in a reservoir, but which are not designed to have any water pass over m; (*b*) spillway dams.

668. **Impounding dams** (Fig. 72) are almost invariably of the gravity e depending on their own weight to resist the forces of the water except the rare cases where ved dams have been built ending wholly or in part arch action. The present ctice is tending toward vy earth dams.

669. **Spillway dams** (Fig. may be further subdi- ed into gravity types and se depending, through ir design, on the hydro- tic pressure of the im- nded water to hold them inst the river bed, and h dams. The arch dam is y economical of material requires that the abut- nts be founded in strong d material capable of ing up the thrust.

670. **Coffer dams** accord- to their height, the nature the bottom and the ex- ure of the location to rent or wave action are structed in a great number rays. Some of the more mon methods are men- ed. Interlocking sheet l piling, and single or ble rows of wooden sheet ng with a puddled filling ween the two rows, are ns frequently used. For cofferdams the A-frame ered with gravel; or bags filled with sand piled in ful rows have been successfully employed. The design of cofferdams is ed on the same principles of hydrostatics governing the design of any er dam.



For effect of upward pressure see Spillway Dam

FIG. 72.—Reservoir dam.

671. **Design of dams.** The conditions which should be safely met by all ıs are stated briefly as follows: (*a*) the dam must not slide; (*b*) the dam ıt not overturn; (*c*) the dam must not crush. The external forces acting the water pressure, the weight of the material composing the dam, the :tion of the foundation, ice pressure near the top, and wind and wave ssure. The pressure usually figured is that of the greatest known freshet, the toe of the deepest section, without backwater. The cross-sec- of the dam is determined by trial. A tentative section is assumed and ı all the forces are computed. If the dam as first designed cannot sfy all the conditions of safety or is unduly heavy it is modified accordingly.

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In the case of the high dams of the gravity type (Fig. 72) it is customar to assume the dam divided by horisontal joints, the depth of each sectio chosen according to judgment in each case, and to treat the sections arbitra ily so selected progressively beginning at the top, testing each for sliding overturning, and crushing. In this way a resultant line of pressure may b traced. In the design of masonry dams it is customary so to proportio the section that the resultant pressure at all horisontal joints shall fall withi the middle third whether the reservoir be full or empty. Thi gives a factor of safety of two against overturning, and ther will be no danger from tensile stresses on the face of the dam There is rarely any trouble experienced, when proper con struction methods are used, from sliding within the bod of the dam itself. The joint between the dam and it foundation is the critical point at which to guar against sliding. It is in this connection that th amount of upward pressure becomes of vita importance. On ledge foundations, steps c trenches should be cut to ensure a sufficien bond. On poorer foundations the dam mus be made massive enough to safeguard again sliding by keeping the angle between th resultant pressure on the base and a vert cal line, less than the angl of sliding of the foundatio material. There is no dange from crushing in dams othe wise stable, except in ver high dams which are no treated here.

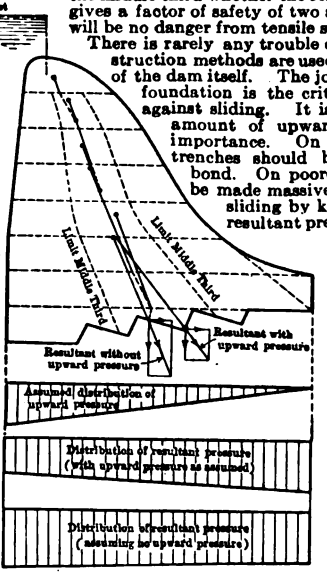


FIG. 73.—Spillway dam.

Dams which depend o the hydrostatic pressure o the water to hold them i place (Fig. 74) may be mad much lighter than the soli masonry dams. The princ pal calculations for strengt involve the deck treated as reinforced slab and of th buttresses as walls subjecte to simple compression. Fi 74 illustrates the action the resultant pressure. a floor is used weep holes a provided to allow any seep age to escape unobstructed

For a more thorough and comprehensive treatment of dams referen should be made to chapter XXIX. "Principles of Construction of Dams in "Water Power Engineering," D. W. Mead (McGraw-Hill Book Co and to "The Design and Construction of Dams," Edward Wegmann (Wile & Son).

672. Upward pressure on the base of a gravity-type dam (Fig. 7 should receive most careful study. The limiting conditions are, on the on side, a tight impervious bottom with the dam so set and keyed into it tha no leakage can occur under the dam. This in effect assumes an unbroke water-tight wall extending from below the bed of the river up to the crest the dam. The other extreme would be a dam founded on loose gravel porous rock which freely admitted the water under the entire base of th dam, but at the downstream toe a cut-off wall would prevent the water fro escaping.

In the first case the assumption is no upward pressure whatever, in th second there would be pressure due to the full hydrostatic head uniformly distributed over the base of the dam. Rarely, if ever, can either of thes cases be found in the extreme form suggested. The truth in every case doubtless between the two. In other words there is probably no dam exis ing without some upward pressure, its extent to be determined only by most careful examination of the geological formation of the river bed at th dam site and the thoroughness with which the seepage is cut off by cut-o walls, grouting or other preventive measures. Except in those cases where th

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m is founded on ledge rock which gives undoubted evidence of soundness d extent, borings are the essential preliminary to the study and design of dam. No rule can be given as to the number of borings necessary but in general way there should be enough to cover the area not only of the spill-y section in the river bed, but also of the abutments and wing walls; and ther structures near the ver; undermining here may rove quite as disastrous as nder the spillway section.

In the case of pervious undations it is desirable to rry a cut-off wall or spiling the upstream toe down to an pervious stratum. Where ch does not exist the wall ould be carried to such a pth that the friction opposg the flow of water will nder the seepage under the m inappreciable. It is good ctice in designing and ilding dams to eliminate so as is possible the leakage ich causes upward pressure, to assume in the computaons for stability the existence full upward pressure at the pstream side diminishing iformly to zero at the downam toe.

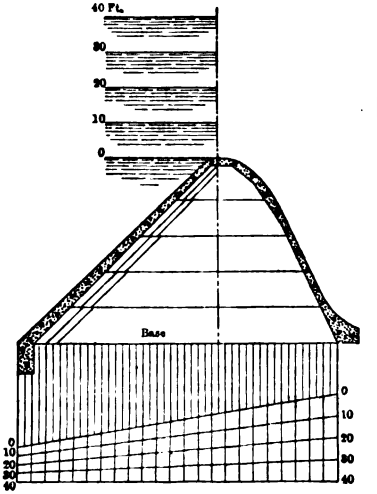


FIG. 74.—Concrete-steel dam.

673. **Earth dams** are perps the most common type d are ordinarily the cheapt. They can be built on most any **foundation** as t-offs and sufficient thickss together with proper selecn of materials will give the ecessary imperviousness. No rth dam is absolutely impervious but the design and construction should such that the water level will remain well below the downstream face of dam. Imperviousness is usually obtained by mixing clay with the loam, d or gravel used for the construction.

If the foundations are not impervious, sheet piling, a **core wall** or a trench ed with impervious material should be provided to prevent undue seepage. ore wall of concrete is sometimes used extending from bed rock to above water level. They are frequently from 2 to 4 feet thick at the top, with a tter of 1 to 10 or even less. Such a core wall should be placed as far upeam in the embankment as possible, since in case it should prove to be pervious the water pressure against its face would greatly exceed that on e downstream side. On this account a core of puddled clay is preferred some engineers. This is usually from 4 to 8 feet thick at the top and at st one-third the depth of water at the bottom.

674. **Dimensions of earth dams.** The dimensions and slopes of rth dams depend on the material and method of construction. For rolled bankment a top width of $(h/5) + 5$, where h is the height of the dam in t, has been suggested. An upstream slope of 3:1 and a downstream slope 2.5 : 1 usually represents good practice. The upper slope should be ed on account of wave action. Beams placed 30 to 40 feet apart vertiy are desirable in high earth dams, as they provide for lateral drainage also give an extra factor of safety against sliding of the embankment. spillway must be provided with earth dams of sufficient length to handle maximum flood without the water rising high enough to overtop the th embankment. Sometimes it can be cut in rock at one end of the earth a, but if this is not possible a masonry or timber spillway is necessary precautions should be taken to secure a good union between the earth bankment and the spillway abutments.

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675. The design of canals for power purposes should be made from economic viewpoint. Canals are employed to utilise a greater head than obtainable directly at the dam and must be built to give the greatest bene at the least cost. Head, the very object of the canal, is often unnecessar lost through poor design of the cross-section and alignment, or through p mitting unnecessary roughness of the bottom and sides. Some slope will required to carry the water through the canal. This should be provided the canal bottom itself unless the drainage must be in a contrary directio otherwise an extra loss of head will result, for the slope of the water reduce the stream cross-section and necessitate a higher velocity to pas given quantity of water. The form of the cross-section must be determin by its requirements and the character of the material. The form should such that it will remain as first built and not wash or slide. In general relatively wide and shallow canals should be avoided because with any dra ing down of the head, or with an ice cover the net area suffers a greater p portionate reduction than in the case of deeper, narrower canals. The vantage of the deep canal can also be shown from a consideration of the for ulas for flow, which show that for a given area the section with the small wetted perimeter will give the best results. The velocity should be k low and as uniform as possible. If there are changes they should be m gradually and in general a velocity once gotten up should be held. The sa statements apply to ditches whether for irrigation or power.

676. Flumes. The word flume implies a narrow waterway with verti or nearly vertical sides. It was formerly used to designate the canal or p stock conveying water to the wheels at its end. In modern practice a flu is understood to mean an aqueduct of relatively small dimensions construc usually of timber or concrete employed to carry water long distances. T interior surface is in general smooth and water is carried at a high velo on an even grade. In computing the carrying capacity of such structu loss by friction predominates.

677. Head-gates are usually installed at the entrance to a canal to c trol the amount of water let in, or to shut it off entirely in case repairs necessary in the canal. They should be strong enough to permit the wa to be entirely drawn out of the canal and to protect the plant during h water. The number and size is fixed by the quantity of water and s structural limitations as weight and strength may impose. Head-g are either hand or power operated according to local circumstances; modern requirements are demanding motor hoists. In designing the p it is usually well to provide for stop logs for occasional repairs to the ga Whenever possible the gates should be so set that the water from the ri enters at low velocity without sharp contraction or change in direction.

678. Booms either floating or fixed are usual to prevent floating d from reaching the head-gates, and in northern rivers ice is also diverted o the dam or through special iceways by this means.

679. Penstocks are frequently used instead of canals or in conjunct with them, the choice depending on cost in the case of low-head to mediu head plants. In high-head plants penstocks and pressure tunnels beco the only way for conveying water from high elevations down to the po house. Penstocks are usually built of riveted steel plates, wooden sta or reinforced concrete, depending on local conditions. They must be signed for strength and carrying capacity. Structurally they must be s to withstand the pressure due the head plus the effect of water hammer also, when empty or partly filled, be strong against collapsing. In k penstocks great care must be taken to provide against **water hammer.** the first place, the thickness of the shell should be selected with this in m and, secondly, provision should be made to take care of the surges when t occur. Where the head permits, the most satisfactory protection is given **stand-pipes** or **surge tanks.** Further protection is given by **relief val** and **blow-out plates,** usually placed just outside the power house.

The thickness of riveted steel penstocks necessary to withstand wa hammer may be computed as follows:

$$t = \frac{(p + p')r}{15{,}000\, e} \quad \text{(in.)} \qquad (1$$

where t = thickness of the shell in inches (should never be less than 0 inch), p = intensity of internal pressure in pounds per square inch, p' additional pressure in pounds per square inch allowed for water hamm r = radius of the penstock in inches, and e = efficiency of the riveted joi which varies from 0.5 to 1.

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Values of p' to be used in above formula (Eq. 131)

Nominal diameter of pipe (in.)	p' (lb. per sq. in.)	Nominal diameter of pipe (in.)	p' (lb. per sq. in.)
16 and 18	100	30	80
20	90	36	75
24	85	42 to 60	70

In designing penstocks for carrying capacity, the velocity to be allowed ll depend, as in the case of canals, on the value of the head saved by ldditional expenditure in the original construction. The problem must be ndied in the light of this consideration and the size of penstock selected cordingly.

680. Cost data. The cost per developed kilowatt of different hydraulic ructures varies very much with the type and character of the development; d is relatively less where the power can be generated near the dam or the tput is large by reason of a high head or a large dependable flow. A typical velopment representing fairly average conditions for a built up fall is:

Item	Per cent. of total cost	Cost per kilowatt on 25,000 kw. equipped (Spring of 1921)
Property	19.3	$48.00
Dam	11.6	29.00
Canal	42.3	105.20
Power house and foundations	9.6	24.00
Equipment	17.2	42.80
Total	100.0	$249.00

Note that the cost of the canal in this case is two-fifths of the entire cost; t this is usually the case unless a portion of the fall is left undeveloped. Steam relay, to supplement dry-weather flow, will add 30 per cent. more the total cost.

681. Forebay and racks. The forebay, where water wheels do not aw directly from the canal or penstock, is an enlargement of the canal ding directly to the racks of the power house which is built across the er end. The power house should be set so that the water flows from the al and passes through the racks with slight if any change in direction. ere is necessarily some loss of head in getting the water through the racks d this should be minimized by setting them so that they draw the water ectly, as mentioned. Provision must be made by a waste weir and channel placed that when open a strong surface current will be created making easy to float accumulated débris and ice away from the racks and dis- arge them into the river.

Racks are customarily built up of flat iron bars from 1/4 to 1/2 in. thick d 2 to 3 in. wide, spaced an inch and a half or more apart in the clear, th the flat side parallel to the flow. The spacing will depend on the e of the water wheels and the fineness of the material to be excluded. e rack should be sectionalized into panels which can readily be ted out for repairs. They should be set at an angle of approximately deg. from the vertical in order to facilitate cleaning with a rake from a atform extending the length of the intakes to the power house. They ould be designed of sufficient strength to withstand the water pressure a dam in case they become completely clogged or frozen up. In cases ere every effort is made to save loss of head, rack bars are made with unded edges or of lenticular shape. There is inevitably some contraction the streams of water in passing through the racks, which should be allowed r in computing the net area to be procured. The velocity through the racks ould be kept low, even when partially clogged. Three feet per second ould be the maximum allowed under the very worst conditions.

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WATER-WHEELS

682. Hydraulics of water-wheels. Force is required to change th velocity and direction of any moving body. In the case of hydraul turbine motors water is the moving body and the water-wheel (whether in pulse or reaction, or combined) is the agent by which the velocity an direction are changed and useful work derived from the process. Th portion of the reduction in velocity not chargeable to friction or other losse occurring during the passage of the water through the buckets is a measu of the efficiency of the wheel as a prime-mover. If a jet of water impinge on a moving vane or bucket, assuming a condition of no friction, the bucke will acquire a velocity equal to that of the jet, *i.e.*, the theoretical velocit due the head acting. The velocity of the wheel must be considered that c the centre of application of all the filaments of water. Under this condi tion, where the velocity of the bucket and of the jet are the same, the je can exert no pressure on the bucke and no work is done. Actually th bucket velocity must in any case be de creased by friction from that suppose above, and the water must exert a least a corresponding amount of pre sure. If now the velocity of th bucket be further decreased until it i blocked, the water is exerting its max imum pressure but again no work being done. There is some speed o rotation between these two extrem at which the maximum amount work will be done; that is, the max mum portion of the velocity of th moving water will be converted in useful work. At this point the moto is running at maximum efficienc Although the buckets and vanes ma be simple or complicated, the abo fundamental conception holds tr and the performance of the wheel ma be analysed by a study of the velocity diagrams at the entrance and exit of the buckets or vanes. This analysis is indicated in Fig. 75.

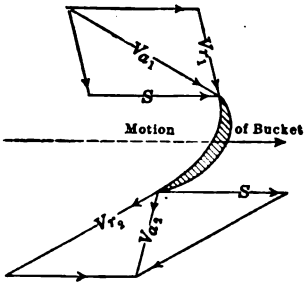


FIG. 75.—Velocity diagram of a water-wheel bucket.

In this diagram S is the peripheral velocity of the bucket, V_{a_1} is t absolute velocity of the water at entrance, V_{r_1} is the resultant of these t and is the relative velocity of the water at entrance. V_{a_2} and V_{r_2} are t absolute and relative velocities at exit. It is the object of good design make V_{r_2} such that V_{a_2} shall be as small as practicable. But this can so fixed for only one condition of speed and gate opening. It is this whi makes it important to know in advance the conditions under which th wheel is to operate.

683. Types of water-wheels. Modern water-wheels may be classifie either as reaction or impulse wheels. While the same fundamental theori hold for each, as pointed out in Par. **682**, the outward form and the metho of utilizing the water are radically different in the two types. The **reaction wheel** (turbine) utilizes in the main the pressure of the water and th reactive force on the curved buckets which tend to change its direction An **impulse wheel** utilizes the velocity and impact of a jet of water directe against buckets on the rim of a wheel. The two types are primarily adapte to widely different conditions: the reaction wheels are best adapted to re latively low heads and large quantities of water; the impulse wheel to hig heads and small quantities of water. In recent years reaction wheels hav been used for all ranges of head up to 600 or 700 ft., where the units ar large. But for heads upwards of 200 ft., with small flow, the impuls wheel of the Pelton type is the natural selection.

683a. Type characteristic. The general design and shape of the guide and buckets of a waterwheel determine the relation between the speed o revolution, the horsepower and the head acting on the wheel. This relatio is called the type characteristic and is expressed by the following equation

$$K = \frac{R.P.M.\sqrt{H.P.}}{H^{5/4}} \qquad (131a$$

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ere K is the type characteristic, $R.P.M.$ the revolutions per minute, $H.P.$ horse power and H the head in feet. The various sizes of a given type waterwheel have the same K within small limits, the speed at which the eel must be operated for a given head decreasing as the diameter or horse-wer is increased. The following table shows average values of K for ious types of American waterwheels. For relatively high speed or large wer a wheel with a high characteristic must be chosen.

lues of Type Characteristic, K, for certain American Turbines.*

Name of manufacturer	Type of wheel	K
llis-Chalmers Mfg. Co.	Type 15	75
llis-Chalmers Mfg. Co.	Type 12	86
ellman-Seaver Morgan Co.	Type A	93
ellman-Seaver Morgan Co.	Type B	66
ellman-Seaver Morgan Co.	Type D	27
mes Leffel & Co.	Type Z	104
mes Leffel & Co.	Samson	62
olyoke Machine Co.	Type B Hercules	66
olyoke Machine Co.	Type D Hercules	78
P. Morris Co.	Type O	91
P. Morris Co.	Type M	69
Morgan Smith Co.	Type K	66
Morgan Smith Co.	Type S	106
ayton Globe Iron Works	Improved New American	80
ayton Globe Iron Works	New American	52
att Iron Works	Victor	60

*Values given are for particular installations. The value of K may ally vary over moderate limits with equally satisfactory operation. arly all manufacturers make several types of runners to cover a wider ge of values of K, a very few types only being given above.

83b. The performances of reaction wheels of various types made by manufacturer under one foot head are given in the following table. any other head (H) the corresponding quantities can be found by tiplying the discharge as given in the table by $H^{\frac{1}{2}}$, the speed by $H^{\frac{1}{2}}$ the horsepower by $H^{\frac{3}{2}}$. Stock sizes of waterwheels ordinarily extend m 12 in. or 15 in. diameter to 72 in. and 100 in., but special wheels have n built with a diameter of 11 feet and over. There is some variation in practice of the different manufacturers in the method measuring the meters of wheels.

Characteristics of Standard Reaction Turbine Runners*

Diam. inches	Type A Specific speed K = 13.55			Type B Specific speed K = 20.3		
	r.p.m.$_1$	h.p.$_1$	Q_1	r.p.m.$_1$	h.p.$_1$	Q_1
15	71.7	0.0358	0.38	76.7	0.0705	0.791
18	59.8	0.0514	0.55	64.0	0.105	1.10
21	51.2	0.0705	0.75	54.7	0.1385	1.45
24	44.75	0.0915	0.975	47.8	0.182	1.91
27	39.8	0.116	1.235	42.5	0.229	2.41
30	35.8	0.1425	1.52	38.25	0.284	2.982
34	31.65	0.184	1.96	33.8	0.363	3.82
38	28.25	0.23	2.442	30.2	0.453	4.78
42	25.65	0.28	2.98	27.4	0.551	5.80
46	23.40	0.336	3.58	25.0	0.665	7.00
50	21.50	0.398	4.24	22.9	0.790	8.40
55	19.56	0.48	5.12	20.9	0.950	10.00
60	17.90	0.573	6.10	19.1	1.130	11.90
65	16.55	0.672	7.15	17.65	1.330	14.00
70	15.40	0.785	8.35	16.40	1.535	16.15

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Characteristics (*Continued*)

Diam. inches	Type C Specific speed K = 29.4			Type D Specific speed K = 40.7		
	r.p.m.$_1$	h.p.$_1$	Q_1	r.p.m.$_1$	h.p.$_1$	Q_1
15	81.5	0.130	1.35	85.6	0.226	2.38
18	68.0	0.187	1.95	71.5	0.324	3.42
21	58.2	0.225	2.34	61.3	0.442	4.64
24	51.0	0.333	3.46	53.55	0.577	6.08
27	45.2	0.423	4.40	47.6	0.731	7.70
30	40.2	0.520	5.40	42.8	0.902	9.47
34	36.0	0.668	6.95	37.8	1.158	12.20
38	32.2	0.835	8.68	33.8	1.444	15.20
42	29.1	1.016	10.55	30.6	1.765	18.50
46	26.6	1.225	12.78	27.9	2.120	22.3
50	24.4	1.450	15.10	25.65	2.50	26.3
55	22.25	1.745	18.10	23.30	3.04	32.0
60	20.4	2.08	21.60	21.40	3.61	38.0
65	18.8	2.44	25.40	19.80	4.22	44.2
70	17.5	2.82	29.40	18.35	4.90	51.5

Characteristics (*Continued*)

Diam. inches	Type E Specific speed K = 49.7 – 62.8			Type F Specific speed K = 70.0 – 83.85		
	r.p.m.$_1$	h.p.$_1$	Q_1	r.p.m.$_1$	h.p.$_1$	Q_1
14	94.6	0.277	2.95	110.9	0.410	4.53
16	83.6	0.367	3.90	97.0	0.541	5.96
18	74.3	0.471	5.02	86.8	0.704	7.77
20	67.0	0.597	6.37	77.0	0.912	10.01
22	61.0	0.731	7.80	69.7	1.133	12.55
24	56.0	0.883	9.42	64.3	1.375	15.20
26	52.0	1.055	11.20	59.5	1.623	17.93
28	48.1	1.243	13.25	55.3	1.930	21.30
30	45.5	1.436	15.30	52.0	2.20	24.30
32	42.7	1.65	17.55	49.1	2.555	28.25
34	40.3	1.89	20.10	46.6	2.825	31.20
36	38.2	2.15	22.80	44.1	3.14	34.75
38	36.2	2.42	25.70	41.9	3.52	38.90
40	34.5	2.75	29.3	39.8	3.93	43.40
42.5	32.5	3.09	33.0	37.5	4.33	47.80
45	30.8	3.53	37.6	35.8	4.92	54.25
47.5	28.8	4.01	42.65	34.0	5.66	62.60
50	27.8	4.45	47.4	32.3	6.13	67.80
52.5	26.6	4.95	52.7	30.8	6.75	74.60
55	25.45	5.52	58.8	29.9	7.50	82.75
57.5	24.3	6.10	65.0	28.2	8.16	90.00
60	23.4	6.80	72.4	27.05	8.94	98.70
64	22.1	7.63	81.25	25.60	10.05	111.0
68	20.9	8.57	91.3	24.20	11.34	125.0
72	19.8	9.58	102.0	22.58	13.07	144.0
76	18.8	10.92	116.0	21.50	14.52	161.0
80	*17.9	12.30	131.0	20.36	16.29	180.0
84	....	.....	.....	19.50	17.88	197.0
88	....	.....	.....	18.60	20.4	225.0
92	....	.....	.....	17.75	22.0	243.0
96	....	.....	.....	16.85	24.48	270.0
100	....	.....	.....	16.30	26.46	293.0

* From "Speed Regulation in Hydro-Electric Plants" by Wm. F. Uhl.

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684. The speed of turbines for a given output and head is confined within quite narrow limits. As noted in Par. **682** there is for any given set of conditions a best speed. This for modern reaction wheels is such that the peripheral velocity is from 0.60 to 0.85 of the theoretical spouting velocity of the water due the head. The best speed may be, and is, varied by design, the recent tendency being toward the development of wheels with high relative velocity; this is easily overdone and is oftentimes secured at the expense of part-gate efficiencies. The best relative bucket velocity in the case of impulse wheels can be shown analytically to be 0.5 and this has been verified by actual tests. Characteristic curves for a modern reaction wheel are given in Fig. 76.

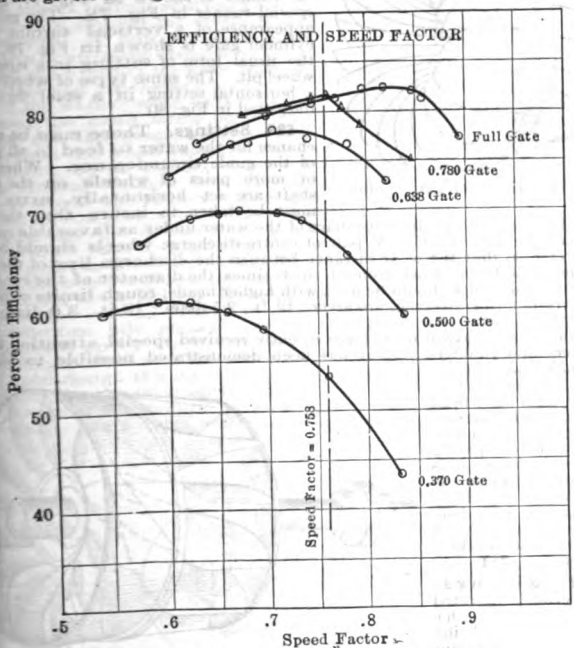


FIG. 76.—Characteristic curves—48-in. turbine.

685. The efficiency of modern water-wheels has been steadily improved by experiment and design until the makers can now guarantee test results of from 80 per cent. to 90 per cent. at the Holyoke Testing Flume (Par. **707**). To get the same result in place requires the best design of the setting and waterways. Many wheels which came up to specification in the Holyoke test have failed signally in place to show the power and efficiency of which they were capable. In most of these cases the fault was not in the wheel but in the setting. A wheel improperly installed is not given a fair chance. By carefully tracing the velocity through the penstocks, wheel case, discharge case and draft tube, using net areas throughout, it is possible to design settings which avoid high velocities and undue changes of velocities and direction, and results in place equal to the Holyoke test results may be expected. Efficiency curves for a modern reaction wheel are given in Fig. 76.

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686. Water velocity through guide chutes. Mention has already bee made of the importance of keeping the velocity of the water through hea gates, canal and racks low. It also should be kept low, not over 3 f per sec., as it approaches the guide chutes of the runner itself. There an exception to this in the case of sing runners set in the so-called scroll cas In these, wheel makers are now requi ing a velocity of about 15 per cent. that due to the head acting on the whee

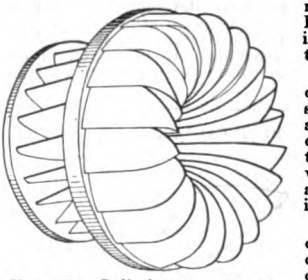


FIG. 77.—Cylinder gate runner.

687. Mechanical details. A typ cal runner is shown in Fig. 77, and special runner in Fig. 78. The gener appearance of a vertical turbine wit cylinder gate is shown in Fig. 79, wit the usual form of setting in a concre wheel pit. The same type of wheel wit a horizontal setting in a steel flume indicated in Fig. 80.

688. Settings. There must be equ chance for the water to feed to all par of the guide circumference. When o or more pairs of wheels on the sam shaft are set horizontally, extra ca must be taken to insure that the la wheel in the line can draw its share of the water under as favorable cond tions as the first wheel. A pair of centre-discharge wheels should be s in the case so that the clear distance between the discharge lips of the tw runners shall be at least from 3 to 4 times the diameter of the runne The greater distance should be used with higher heads; rough limits of hea and corresponding distances are given: 12 ft., 2.5 diam.; 18 ft., 3.0 diam.; ft., 3.5 diam.; 50 ft., 4.0 diam.

Single, large, vertical units have recently received special attention fro designers and builders, and it has been demonstrated possible to obta efficiencies with them about 4 per cent. higher than have been obtained with horizontal settings of equal output. In comparing different settings it is important to know exactly where the head is measured; it is here assumed that the net effective head is taken. See also Par. **711**.

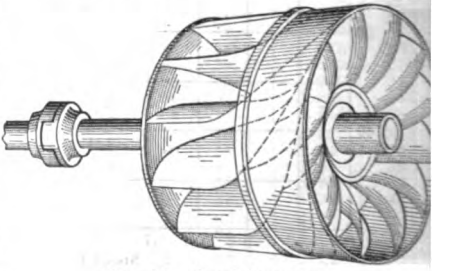


FIG. 78.—Special runner.

689. Ratings. Water-wheels are rated in horse-power, the rating given being usually the maximum output under the head stipulated. It is important to keep in mind three things: (*a*) that a horse-power is a small unit than the kilowatt (1 horse-power = 0.746 kw.); (*b*) that water-whee driving generators must carry the normal load at from 0.75 to 0.80 ga in order to take care of overload on the generators; (*c*) when once under given head the wheel is discharging its maximum quantity of water further output can be wrung from it. The attempt to impose a heavi load can only result in reduced speed and output. Simplification wou result if water-wheel ratings for hydro-electric plants were stated kilowatts and generator ratings were stated in terms of the maximum ou put instead of normal rated output. This would remove the sources confusion brought about by rating each half of an integral unit by a sep rate standard.

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690. **Draft tubes** make it possible to set reaction wheels well above tail-ater. This is a distinct and important advantage. It makes the wheels ccessible for inspection and repair in spite of backwater conditions, and ermits the use of horizontal wheels direct-connected to generator or shafting ithout sacrificing head. In a plant subject to severe backwater, if the achinery floor can be set 20 ft. above low tail-water elevation, draft ibes frequently save great expense in heavy construction and waterproofing f the power house.

A reaction wheel discharging freely into e air would be acted on by a head equal the distance from headwater elevation the elevation of the centre of the dis-arge orifices, minus such losses as occur. he pressure against the discharge is full mospheric. If now we attach an air-ght pipe of suitable diameter to the run-r case and conduct the water down from e wheel and discharge it under the sur-ce of the water in the tailrace we have creased the head acting on the wheel, ecause now the pressure against the dis-harge from the wheel buckets is less than tmospheric by an amount corresponding the vertical distance from buckets to ailrace, where the full atmospheric pres-re acting on the water in the tailrace holding up the column of water in the ipe or draft tube so-called (Fig. 82). A rther gain is effected by gradually en-arging the cross-section of the draft tube. his reduces the velocity of discharge and ome of the energy present as velocity transformed into pressure within the draft tube. This increases the olumn held up by atmospheric pressure acting on the tailwater and cor-espondingly decreases the pressure against the discharge from the wheel. ith good design this may amount to a foot of head. The flare should not e greater than approximately 1 in 10.

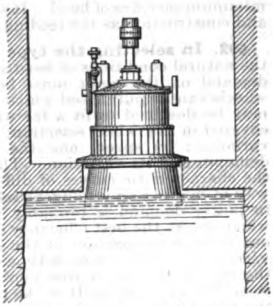


FIG. 79.—General arrangement of vertical turbine with cylinder gate.

The normal atmospheric pressure will support a column of water 34 ft. height. Draft tubes are seldom used longer than 25 ft. There are

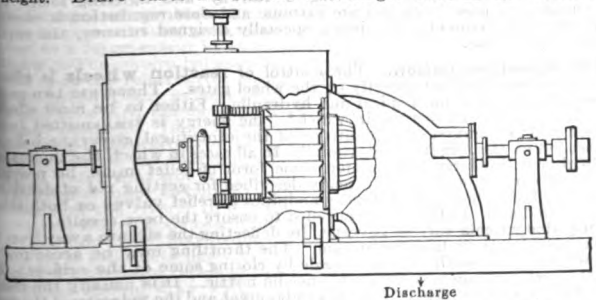


FIG. 80.—Cylinder gate turbine, horizontal type in steel flume.

tructural limitations, inevitable losses and some leakage of air which akes it difficult to maintain to any greater height an unbroken column f solid water, essential to the success of the tube. It has been noted that he pressure within the draft tube is less than atmospheric. This necessi-ates an air-tight design suited to withstand collapsing pressure.

The velocity through the upper portion of the draft tube is necessarily igh. For this reason, the interior surface should be smooth to minimize

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friction and eddy losses; and in the case of horizontal wheels the obstructi caused by the shaft should be made as slight as possible. If draft tubes s set on an angle it should never be more than 45 deg. from the vertical. T elevation of the outlet should be fixed so that the draft tube shall be seal during lowest tailwater conditions. The velocity of discharge from the tu should in general be a little greater than that of the water into which it d charges, but ordinarily not more than 3.5 or 4 ft. per sec. at full discharge.

691. The tailrace should be designed to carry the water away with minimum sacrifice of head. It should therefore receive the same care in desi and construction as the feeding canal.

692. In selecting the type of wheel to be installed in any power pla the natural conditions of head and flow, with their variations, and the pow demand on the plant must be clearly and definitely understood. Sto wheels can be purchased which fit a wide range of conditions; special whe may be designed to fit a far wider range. The following points should covered in any wheel selection: (*a*) head, and its variation; (*b*) flow, and variation; (*c*) speed, and the importance of close regulation; (*d*) pow demand, and its variation. These may best be studied in connection wi the characteristic curves of different types of turbines; it is in fact the on way of making an intelligent selection from stock designs. The fluctuati in power demand is probably the most troublesome point and the wh which shows the best efficiency over the desired range may be readily pick out from a comparison of the curves. In the same way the effect of t variations of head on each type of wheel may be seen and allowance made the choice. A set of common characteristic curves are shown in Fig. these are drawn from Holyoke test results, reduced to the head under wh the wheel is to operate.

Three examples are given below to illustrate three typical but varia requirements which water-wheels have met successfully. The number units should be based upon the fluctuations in stream flow and power d mand; but each unit should be ready to take care of momentary fluctuatio

(1) Ground-wood pulp mill. Here the wheels are run at full gate as lo as there is water to run them. High speed is important, but moderate var tions in head are of small concern.

(2) Textile mill. There is only moderate variation in load during worki hours. Uniform speed is vital; therefore wheels which hold their efficien for constant speed under variations of head are desired.

(3) Hydroelectric plant carrying a railway and lighting load. He fluctuations in power demand are extreme and close regulation is essenti Such a plant frequently requires a specially designed runner; the requir ments are obvious.

693. Speed regulation. The control of **reaction wheels** is effect by governors which act directly on the wheel gates. There are two gener types of governors, mechanical and hydraulic. Either to be most effecti should be of the relay type in which* "the energy is transmitted from source independent—as to quantity—of the centrifugal governor balls b controlled by them in its application." In all cases in which the fluctuatio in load may be large and sudden some form of relief must be provide For open canals the spillway already described for getting rid of débris w answer. For long penstock lines standpipes or relief valves or both shou be provided and careful study is needed to ensure the best results.

Impulse wheels may be governed by deflecting the stream away from t buckets or by throttling the stream. The throttling may be accomplish in the case of a multiple orifice nozzle by closing some of the orifices. T usual nozzle is known as the Doble needle nozzle. It is usually the case impulse wheel installations that the head is great and the velocity of the wat high. For this reason the inertia of the column of water contained in t penstock is such as to prohibit, on the grounds of safety, governing b throttling alone. In such cases the first action of the governor is to defle the stream, the second and slower action is to throttle the flow. This com bined control is the most economical of water.

* Mead, D. W., "Water Power Engineering;" New York, McGraw-Hi Book Co., Inc., 1908.

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4. **Governors** have been developed and improved rapidly in recent
s. The increasing demand for close regulation of power plants has
ulated this improvement until now there is a new type fitted to every
requirement. In general it can be said that for small units and for cases
hich the textile plant is representative the mechanical governor is ad-
bly suited. For large units such as are becoming common in hydro-
ric practice the hydraulic governor is better fitted to develop the great
necessary to operate the turbine gates. According to Mead* governor
fications should call for a guarantee of the following: (*a*) sensitiveness
r cent. load change which will actuate the governor; (*b*) power which
overnor can develop and force which it can exert to move the gates;
pidity with which it will move the gates; (*d*) anti-racing qualities, such
mber of gate movements required to adjust for a given load change;
neral requirements of material, strength, durability, etc. The hydraulic
eer can simplify governing to a marked degree by good design of the
ocks, draft tubes, etc

5. **Operation.** The cost of operating a hydroelectric plant is from
15 per cent. of the first cost.

6. **Cost data.** A sub-division of costs (Spring of 1921) for a typical
is as follows:

Item	Per kw. year
est 6 per cent. on $249.0 (Items 1–5, Par. 680)	$14.94
eciation 10 per cent. on 42.80 (Item 5, Par. 680)	4.28
per cent. on 53.0 (Items 2 and 4, Par. 680)	1.06
per cent. on 105.20 (Item 3, Par. 680)	1.06
ary repairs and maintenance $5½ per kw. year	5.34
nistration $2.00 per kw. year	2.00
2 per cent. on $150.0 (60 per cent. of total cost)	3.00
ance ½ of 1 per cent. on $66.8 (Items 4 and 5, Par. 680.	0.34
	$32.02

te that interest at 6 per cent. and depreciation are two-thirds of the
Steam relay to supplement dry-weather flow will add 25 per cent. to
ting cost *without coal*, if charged against the water power.

PLANT DESIGN

7. **General ensemble.** The location and relative position of the dam,
works, power house, tailrace, and all other necessary structures must be
ned to a large extent by the topography and the geological conditions
e site. The choice between various possible schemes will be based in
ain upon the relative cost considered in connection with the efficiency
e proposed plant as an energy producer, or as an income producer.
eight to which the dam may be built is usually limited by the extent
wage damage. In a hydroelectric plant pondage may have great
, making fully warranted the purchase of extensive flowage rights. The
ay section of the dam should be designed to pass safely the maximum
nt of water that can be expected. Likewise the abutments and other
structures must be built to withstand successfully the greatest freshet
ivable on the river. In this connection it is important to realise that
extraordinary flood conditions the channel above and below the dam,
ot the dam itself, may frequently control the height to which the water
This is especially likely to be the case when the dam is built at the
of rocky tortuous rapids or in a bend of the river.
e intake should draw water from the stream with as little change in
tion as feasible and must be protected by some form of boom which
direct ice and floating débris away from the head-gates and over the dam,
rough a waste channel designed for that purpose. Additional head may
tained over that at the dam itself by carrying the water downstream in
s or penstocks. The advisability of such procedure is determined by
dy of the fixed charges on the structure and the value of the increased
y so obtained.
e whole system of waterways from head-gates through the canal or
ock, racks, wheelpit and tailrace to the river should be designed to

*Mead, D. W., "Water Power Engineering;" New York, McGraw-Hill
Co., Inc., 1908; Chap. XVIII, p. 467.

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keep the velocities low enough to avoid excessive loss of head. Fluctuation in velocity are bad, and if unavoidable the changes should be made gradually It is better to gradually speed the water up from say 1 ft. per sec. the head-gates to not more than 3 ft. per sec. at the wheel gates, i the case of the ordinary vertical or horizontal setting; the exception in th

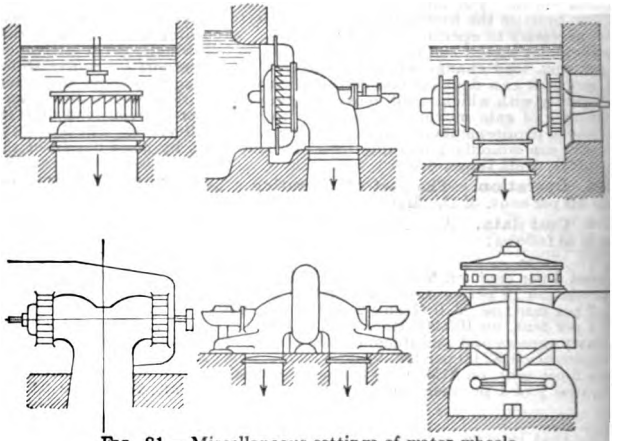


FIG. 81.—Miscellaneous settings of water-wheels.

case of scroll case settings has been noted in Par. 686. Where more than wheel is mounted on a shaft it is important to provide for equal distribut of the water among the units, and to provide against interference the draft chest as mentioned in Par. 688. The velocity at the top of draft tube is necessarily high and sho be gradually reduced by enlarging cross-section of the tube until it is d charged at about 3 ft. per sec.

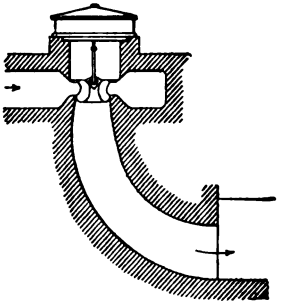


FIG. 82.—Single vertical turbine in a spiral flume direct connected to a vertical electric generator.

698. Typical settings of water whe are shown in Fig. 81. A modern form setting known as the spiral or scroll c ing is illustrated in Fig. 82, which sho a longitudinal vertical cross-section. T latter type of setting is employed at Keokuk plant of the Mississippi Ri Power Co.

699. The economical developm of a water-power proposition must depe upon the available power in the riv the market, and the degree to which au iary power is to be employed. Two thi must be determined as exactly as possi (*a*) the hydrograph of the river (P 688); (*b*) the load curve.

A thorough and exhaustive study of run-off data should be made where th are available; otherwise study must made by comparison with similar drain areas by means of rainfall data. Ex ing and possible storage should receive careful attention. It should be membered that on streams with incomplete storage *averages are danger* leading to overdevelopment. Two or 3 days of flood discharge in a mo

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much above the capacity of any possible equipment can raise the monthly average to give a totally erroneous impression of the kilowatt hours available. For this reason, daily records of flow should be used in preference to monthly records, since the daily records bring out the maximum and minimum flows and the final estimate can be much nearer the truth.

The probable load curve is of prime importance, and taken together with the available pondage it will determine the number and size of units to be installed to give flexibility and economy in operating.

700. Auxiliary power. If a relay station, steam, gas or oil, be used, it should be placed as near the market or sources of fuel as economic conditions warrant. Its capacity must be determined by the daily and yearly hydrograph and the load curve. So many combinations of conditions of pondage, storage and load occur that every case must have special and detailed study. There are very few developments where a relay station owned either by the seller or the buyer of hydroelectric energy is not almost essential.

701. Choice of units. With varying load, efficiency requires two or more units so that during the hours of minimum demand the machine or machines on the line can carry the load at good efficiency. Then as the load comes on additional machines are cut in as needed.

702. Provisions for handling floods include: (*a*) **flashboards;** (*b*) **Tainter gates;** (*c*) **sluice gates.** It has been noted that the height to which a power dam can be built is usually limited by the extent of the flowage permissible (Par. **697**). This necessarily applies to the high-water stages which may be expected every year, and settlements for the necessary rights are usually made once for all. During most of the months in each year increased pondage or head, or both, can advantageously be procured by raising the dam without creating greater flowage than occurs during high water from the dam at its permanent elevation. This is accomplished in a number of ways, but most commonly on power dams by the use of flashboards which are designed to bend over or go off during floods. In this way provision is made for handling floods at the moderate cost of replacing the flashboards.

In order to provide for the occasional summer freshet and to give greater discharging capacity in cases of great freshets **flood gates** are incorporated in many modern dams. When warned of a freshet, probably of short duration, it is frequently possible by opening the gates in the dam to pass the extra water without straining or losing the flashboards. Flashboards are ordinarily held in place by either wrought-iron pins which will bend over, or light wooden figure-fours which will break when the water rises too high. The development of water power on navigable streams also leads to the use of Tainter gates, Chanoine wickets, Bear traps and other forms of movable dams ordinarily suited to their purpose, but which in northern rivers carrying much ice must be designed with great care.

703. Log sluices and fish ladders are necessary appendages to most power dams. A log sluice is an inclined chute on the downstream side of the dam with a gate at the crest which is opened whenever a log drive must be run past the dam. These are usually required by law where log driving has ever existed on the river. Fishways are required by federal law on most rivers and must be kept open during certain portions of the year. There are various forms, two of which are mentioned. One is constructed to form a flight of pools, the water spilling into each successively. The other is a chute set at a moderately flat slope with baffles built alternately from the right and left sides, about three-quarters of the way across.

704. Buildings and foundations. The conditions controlling plant design are discussed in detail in Par. **697**, **700** and **701**. Foundations are usually subject to water pressures due to head or backwater or variations from drought to flood conditions. These conditions usually require foundations much in excess of ordinary building requirements.

The size, height and arrangement of buildings usually follow these hydraulic conditions and the type of unit selected.

705. Summary of unit costs. Unit costs common to most water-power developments with some idea of the range of prices (Spring of 1921) which depends upon the amount of each contract, distance from markets, difficulties of handling, etc., are:

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Rock excavation under water	$8.00 to $15.00 per cu. yd.
Earth excavation under water	2.00 to 3.00 per cu. yd.
Rock excavation in the open or behind tight coffer dams	2.25 to 5.00 per cu. yd.
Earth excavation behind tight coffer dams	0.75 to 2.00 per cu. yd.
Coffer dams	10.00 to 20.00 per. lin. ft.
Reinforced concrete	20.00 to 30.00 per cu. yd.
Ordinary concrete	12.00 to 16.00 per cu. yd.
Reinforcing material	0.06 to 0.10 per lb.
Penstock and draft tubes of steel plate, erected.	0.15 to 0.20 per lb.

TESTING

706. Water-wheel testing has played a vital part in the improvements which have been accomplished in the design and construction of turbines. Every water-wheel should be tested if possible before it is installed. That a similar wheel of the same make, diameter and pattern has been tested and shown satisfactory results is no guarantee that a wheel which has not been tested will give similar results. The expense of the test should never be allowed to militate against it, for a gain of only 1 per cent. in efficiency will pay for the test in a relatively short time. Specifications and guarantee requirements should be drawn with care and include where feasible provision for final acceptance tests in place, in addition to the preliminary tests at the Holyoke Testing Flume. In addition to finding out whether the wheel has met the specification requirements, the tests furnish data by means of which the use of the wheel as a water meter is possible (Par. **663**).

707. The Holyoke Testing Flume furnishes the only place in this country where systematic testing is carried on. The maximum head is 17 ft. and the maximum discharge possible is between 250 and 300 cu. ft. per sec., at which discharge the head is reduced nearly one-third. In spite of these limitations the tests are invaluable to the water-power engineer and form a common basis of comparison for designers.

708. The quantities to be measured in a water-wheel test are speed, head, discharge and power output. At the Holyoke flume these are observed by a revolution counter, head and tail water gages, weir and Prony brake, respectively. Various gate openings are selected and for each opening the wheel is run at many speeds in order to determine the most efficient speed for each gate.

709. For making the final acceptance test of water wheels a test in place is becoming more frequent. Such a test furnishes direct evidence of the performance of the wheels under service conditions.

710. The general problem is that of any test of power machinery; namely, to measure the input and the output. To measure the input requires the measurement of the head and the quantity of water used by the unit under test.

711. The points of measurement of the head should be selected to show the net head actually acting on the wheel. Friction losses in canal or penstock and tailrace are not properly charged against the performance of the turbines, however much they may affect the overall efficiency of the plant. The point therefore at which to measure the headwater is just before the water is drawn to the guide chutes, and the tail-water should be observed at the nearest feasible point to the discharge of the draft tube. In open flume settings the head water is observed in the flume. In the ordinary pressure-case setting a gage should be tapped into the side of the penstock (Par. **640**, *piezometers*) just clear of the case in order to avoid disturbances due to eddies and uneven flow in the case. In a scroll-case setting, the scroll, like the draft tube, must be considered an integral part of the wheel and the head should be measured between the entrance to one and the discharge of the other.

712. Measurement of the quantity of water used presents some difficulties unless special provision was made in the design of the plant. It has been usual practice to install a weir in the tailrace. Unless the conditions are exceptional the results are subject to serious but undeterminable error due to the relatively high velocity of approach to the weir (Par. **609** *et seq.*). The attempt is made by building the crest high enough from the bottom to t down the velocity, the head acting on the wheel is thereby reduced and

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at once the actual service conditions are only approximated and the peculiar value of the test in place is partially vitiated. It is difficult to make the conditions of the channel of approach to the weir suitable for good measurements and the expense of installation is relatively great. Whatever method of measurement is used, there should be an agreement in advance by the buyer and seller of the wheels to accept the results. Where conditions for their use are right, rod floats (Par. **643**) afford an excellent means for measuring the flow either in the headrace or tailrace.

The easiest measurements to make properly are probably those with a current meter (Par. **662**). The expense is slight and in the hands of careful and experienced operators simultaneous measurements in head race and tail-race will give excellent results without interfering in any way with the normal service conditions of operation. Suitable measuring stations may be easily included in the original design of the plant at little or no extra expense.

For relatively small units fed by penstocks, the most accurate measurement without question can be made by a venturi meter (Par. **636**) incorporated in the penstock when the plant is installed. When properly rated it has the great advantage of giving a continuous record of flow.

713. For measuring the output two general methods are available for a hydroelectric station. They are (1) to measure the energy generated electrically, or (2) with some form of absorption dynamometer. The electrical measurement requires that the driven dynamo shall have been carefully tested and the efficiency determined for all loads. Electrical measurements can be made with great accuracy but the determination of the turbine output by this means is somewhat indirect. With the development of the **Alden dynamometer** direct and accurate measurement is possible. This apparatus is described as follows by Prof. C. M. Allen:

"It is a form of Prony brake, and usually consists of several smooth circular revolvable cast-iron discs keyed to the shaft which transmits the power; a non-revolvable housing having its bearings upon the hubs of the revolving discs; and a pair of thin copper plates in contact with each cast-iron disc, the plates being integral with the housing. Through a system of piping, water under pressure is circulated through chambers between the units, each consisting of a disc and its copper plates, and between the outer plate at either end and the wall of the housing. The water pressure is regulated by hand or by an automatic valve. Another system of piping circulates oil for lubricating the surface of the copper plates next to the revolving discs."

714. Advantages of the test in place. The test in place, if made complete enough to cover all gate openings under normal conditions of head at the plant, will serve two purposes: it will tell whether the wheels tested are up to specification; and it will provide a means of measuring the daily or hourly amount of water drawn by the plant so long as the wheels are kept clean and in good repair, and the operating conditions are essentially those obtaining during the test. These records if carefully kept become of great value to the owner and operator of the plant.

ELECTRICAL EQUIPMENT OF POWER PLANTS

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ELECTRIC GENERATORS

715. Types of generators are covered in Sec. 7 and Sec. 8.

716. Generator characteristics required for a given power plant are largely determined by the size, overload capacity, speed, speed variations, and possibilities of over speed of the prime mover; the size of the plant, the number of units, the load factor, fluctuations and power-factor of the load; the voltage and type of the distribution system.

717. Sizes of generators. The ratio between the adjacent sizes of generators varies from 1.25 to 1.50. The size limitations seem to have been reached only for direct-current generation, where 2,700 kw. is the largest obtained commercially. Engine-driven alternators are in operation which will

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carry from 8,000 to 10,000 kv-a. continuously without overheating. Water wheel alternators are built up to 32,500 kv-a. and there is little doubt that larger sizes can be built if required. Steam-turbo-driven alternators are being built up to 45,000 kv-a.

718. Overload capacity in generators is necessary only when the prime mover has ability to deliver loads greater than rating, or in special cases where it is desirable to install a generator smaller than the maximum output of the prime mover. Gas engines which will stop when their rated capacity is much exceeded, require generators which will reach their maximum safe temperature when continuously operated at rated load. This same condition is required of steam turbines when rated at the maximum capacity, and by water-wheels except in very unusual circumstances. Steam engines which are rated at their most economical load, or steam turbines having overload valves, require generators with considerable overload capacity. Generators of the first class are usually designed to carry their rated load continuously with a temperature rise of about 50 deg. Cent. Generators of the second class are designed to carry rated loads continuously with 40 deg. Cent. temperature rise, and 25 per cent. overload with a 55 deg. rise.

719. Speeds of standard designs range from 75 r.p.m. upward, the ratios between adjacent speeds being from 1.1 to 1.2. Low speeds are confined to large machines. Several speeds for the same size are usually available, particularly in small and moderate sizes. The speed of direct-current machinery is limited by commutation. High-speed direct-current generators, even of relatively small size, are not recommended. The speed of alternating-current generators is controlled by frequency and by number of poles. At the high speeds, ventilation becomes one of the principal problems, but the manufacturers have solved it to such an extent that machines are offered in sizes up to 5,000 kv-a. at 3,600 r.p.m. and up to 30,000 kv-a. at 1,500 r.p.m.

High-speed generators deliver short-circuit currents of enormous instantaneous value, even though the sustained short-circuit currents are limited. This characteristic is of greatest importance in large systems particularly in reference to switching methods (Par. **799**).

720. Speed variations or fluctuations in the driving torque have a tendency to accentuate the difficulties of commutation. In alternating-current machines the speed variations are of great importance to parallel operation, particularly when the speed is low and the number of poles is large. The driving impulse in gas engines and low-speed steam engines being non-uniform, flywheels of large moment of inertia are required to keep down the speed fluctuations so that satisfactory parallel operation may be obtained. It is usually necessary to have alternators for this service designed with large armature reaction and reactance, so that the angular variations will produce a minimum of surging in the electric circuits. With gas engines it is necessary to use short-circuited pole-face windings.

721. Runaway speeds. In engines and turbines it is easily possible to provide emergency governors so that generators need be specified to stand only about 30 per cent. overspeed. In water-wheel units, however, the difficulty in caring for the inertia of the water in long pipe lines makes it necessary to have generators safe at 90 per cent. to 100 per cent. over-speed.

722. Inherent regulation. In very small plants good regulation is to be sought for, particularly on account of the lack of skilled attendance, and also on account of the large number of other uncontrollable influences affecting the uniformity of voltage. In the larger plants the question of regulation is of less importance because of better attendance and the feasibility of automatic regulating devices.

In very large plants the importance of keeping down short-circuit currents both instantaneous and sustained, looms up in such large proportions that regulation is completely neglected except as may be necessary to secure proper conditions of parallel operation. In these large plants it is usual to go to considerable expense to secure automatic regulation of voltage allowing generators of exceedingly low inherent regulation. Induction generators and current-limiting reactances (Sec. 6), are also used in many plants to limit short-circuit currents.

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723. The number of units has relatively small influence except as ffecting parallel operation, the conditions of which are more exacting in a lant of many units. (Also see Par. **724.**)

724. The load factor, or the form of the load curve has particular nfluence in determining the number of units to be installed and the overload pacities of the same. With a steady load for 10 hr. per day, generators hould be installed to carry the load with one unit shut-down, without xceeding the overload capacity. With large short peaks for a few months i the year, and much smaller loads during the other months, the peaks can fely be carried at overloads even in excess of 25 per cent. for which nerators are frequently specified.

725. Load fluctuations. If the load is widely fluctuating, such as on lectric railways of few cars, the commutation limit of direct-current achines determines the size to be installed. Interpole generators with bility to commutate loads far above the usual rating are frequently used) that the average load may approach the heating limit. In alternating-rrent machines this question is of less importance, as they are stable at ry considerable momentary overloads. In single-phase railway systems here violent short-circuits are frequent the windings need to be specially haced. Fluctuating loads will cause considerable voltage variation and ay determine the requirements of regulation, particularly in small id medium size plants. Compounding is almost invariably resorted to l direct-current plants and sometimes in small alternating-current plants; ven then there is considerable variation in voltage, especially on rapidly rying loads.

726. The power-factor determines not only the kilovolt-ampere rating the generators to be installed, but also the size and resistance of the field indings. Machines required to carry lagging loads need larger fields than achines to carry leading loads of the same magnitude. Generators are sually supplied with field windings suitable to care for full inductive loads 80 per cent. power-factor. This is usually sufficient to take care of any ndition which may be expected.

727. The voltage. Standard direct-current machines are available at 5 volts, 250 volts, two-wire and three-wire, also at 600 volts, and 1,200 lts; alternating-current machines at the above voltages and in addition 300 volts, 2,300/4,000 volts, four-wire, three-phase, 6,600 volts, 11,000 volts d 13,200 volts. Higher than 2,300 volts, without the use of compensators transformers, is not recommended in small high-speed machines. 11,000 lts and above in turbo-generators, except of largest size, should be avoided, t is entirely safe in slow-speed machines. Other voltages are used at nes but the machines are special. Occasionally it is desirable to use nerators connected in delta at 2,300 or 6,600 volts but insulated for 4,000 11,000 volts, making it possible later to increase the voltage of the system. gh-voltage machines are usually star connected, because of the possibility larger conductors and more rigid windings.

728. Foundations for electric generators are usually parts of those the prime movers. The type and form is largely dictated by the require-ents of the prime mover. It is becoming the practice to support turbo-nerators on skeleton foundations and even directly on the floor with a ement underneath. For the cost and detailed design see Sec. 10.

729. The erection of generators covers a considerable range of work pending upon the method of shipment. Small machines are shipped mpletely assembled and the erection consists merely of placing in position d leveling. With larger units the facilities for transportation and hauling mit the sizes for separate parts and in extreme cases the machines are ipped almost completely dismantled, requiring the most careful work in ecting them and preparing them for preliminary operation by drying and ltage tests.

730. Preliminary operation requires a determination of the polarity or ases, before actual connection to the lines, as well as careful watching and rting during operation necessary to determine whether or not the machine perfect and ready for regular and continuous service. Phases as marked the factory should not be depended upon. Phases and synchronizing

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equipment may be checked by connecting to a spare machine and bus, bringing up to speed with the spare machine and synchronizing by the use of the apparatus on the spare machine. If no spares are available, lamps, alone or with shunt transformers, connected across the open switch may be used. Simultaneous dark lamps indicate correct phases; when lamps do not darken and brighten together crossed phases are indicated.

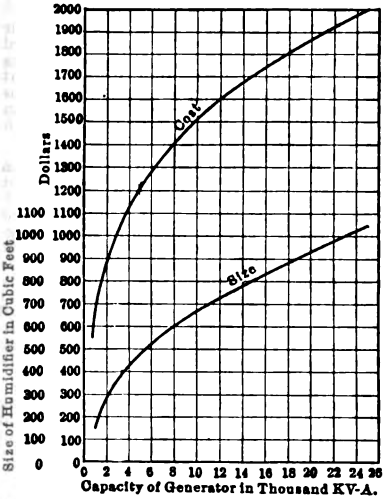


FIG. 83.—Size and cost of humidifiers (*G.E. Rev.*, Sept., 1913, p. 634). (Note: Add 80% To Cost For 1921 Prices).

731. The volume of air required for cooling is generally about 5 cu. ft. per min. per kv-a. of generator capacity.

732. Cleaning the air is a matter of great importance but frequently neglected. Dirt which clogs up the air passages and coats the cooling surfaces prevents proper cooling and shortens the life of the machine. Reasonable cleanness may be secured by having the intake above the roof, thus keeping out all but the finest dust. If the air must be taken from near the ground, it should be filtered by passing at low velocity through one or more thicknesses of cheese cloth or Canton flannel. Complete cleaning requires large areas, amounting to about 1 sq. ft. per kw. of generator capacity. Means must be provided for the ready cleaning and replacement of screens. Water screens (air washers) or humidi-

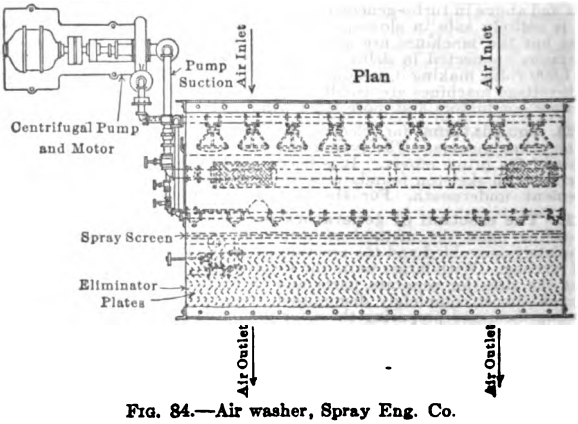


FIG. 84.—Air washer, Spray Eng. Co.

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fers are largely used in which the air is passed through falling water which takes out the dust, and then freed from mist by baffles (Fig. 84). This method has the added advantage of cooling the air several degrees. The value of this may be seen in Fig. 85.

733. The cost of erection and preliminary operation of generators ranges between wide limits depending upon local conditions. Smaller machines which are shipped assembled may cost for erection and preparation for regular service, in reasonably equipped stations, from 4 per cent. to 5 per cent. of the cost of the machine at the factory. If the machine is shipped dismantled, the cost of erection will be about 1 per cent. to 2 per cent. higher. The cost of erecting large machines is from 4 per cent. to 5 per cent., and in a few cases where conditions allow shipment assembled, about 1 per cent. can be saved. (An average pre-war cost, for machines from 500 kw. to 6,000 kw., was $400 per unit plus $0.32 per kw.). For 1921 costs add 100 per cent. Freight and haulage is dependent absolutely on location and local conditions, and may vary from 1 per cent. to 15 per cent. of the cost of the machine.

734. Ventilation. The continued success of ventilation methods has a most important influence in determining the life of the insulation. The requirements call for a plentiful supply of cool air free from dust, oil and excessive moisture. Except in turbo-generators, no special means are taken to fulfill these conditions other than those provided in the machine. In high-speed turbo-generators, however, large volumes of air at enormous speeds are passed through the windings, and the utmost pains should be taken to maintain the best possible conditions. In some stations it is customary to take the cooling air directly from, and discharge it into the turbine room, but in cases where the room cannot be well ventilated, this arrangement may overheat the room and the machines. In other stations it has been found possible greatly to increase the capacity of the generators by installing specially designed vanes on the rotors, thus passing much larger volumes of air. With a machine thus ventilated, the coils quickly become dirty and much care has to be exercised to keep out the oil that permeates the atmosphere. In most stations it has been found important to install ventilating ducts taking cool air directly from outside the building.

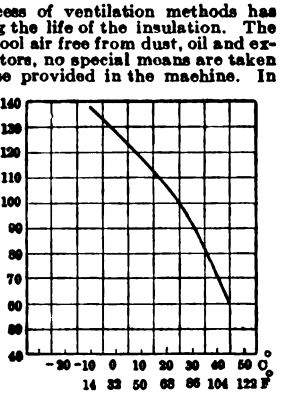


FIG. 85.—Safe load and temperature of cooling air (*G. E. Rev.*, Sept., 1913, p. 633).

The ducts should be of liberal size to keep down air velocities to about 1,000 ft. per min. Dampers should be provided to enable shutting off the air supply in case of burn-outs. Ventilation by separately driven blowers is being used and is strongly recommended by some engineers.

735. The cost of ventilating ducts arranged for cleaning the air would approximate 25 cents per kw. of generator capacity under pre-war conditions or 45 cents for 1921.

736. The operating temperature, combined with the kind of insulation, determines absolutely whether or not the machine is overloaded. Temperatures are difficult of measurement, particularly in respect to finding the hottest parts. It is the maximum temperatures which are of importance, and it is probable that these are never found in tests. Resistance temperature tests are difficult to make, and in large machines take considerable time after shut-down; such tests give only average copper temperatures, which are certainly less than the maximum. Ordinary thermometer tests give the temperature of the outside of the insulation, and by means of refinements it is possible that maximum temperatures can be measured to within 10 deg. to 20 deg. Cent., but this method is not recommended. Resistance thermometers and thermo-couples, inserted between the coils and the iron,

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are used with considerable success. The actual indicator may be located anywhere convenient, even on the switchboard, where continuous record of the temperature may be kept. This method gives more consistent and precise results than the others and probably shows more nearly the maximum temperatures.* Indicating electric thermometers can be installed for $100 to $200 per machine.

737. Safe temperatures of insulation are given by C. P. Steinmetz and B. G. Lamme in the February, 1913, *Proceedings* of the A. I. E. E. as 90 deg. Cent. for fibrous insulation such as is commonly used, and 125 deg. Cent. for mica and other fire-resisting materials. These temperatures are the measurable temperatures rather than the absolute maximum that may be expected in local spots. H. G. Stott recommended 20 deg. lower temperatures, especially on high voltage work.

EXCITATION

738. Excitation equipment should be designed with a view to the maximum possible **continuity of service**. Simplicity, ruggedness, "fool proofness" and reserve apparatus are important requirements. The methods in use for securing these results are greatly varied and much difference of opinion exists as to the best method. Each plant must be considered as a separate problem.

739. Exciters directly connected to the main generators were the earliest form in use. Each exciter is frequently made large enough to handle two generators, in emergencies. The chief arguments in favor of this method are simplicity, high efficiency and the absence of large field rheostats. The most important objections are the possible crippling of a large unit due to trouble with its exciter, and the fact that voltage fluctuations in per cent. are twice as great as the speed fluctuations.

740. Exciters driven by separate prime movers may be obtained for service with any kind of prime mover. On account of their small size the efficiency of the unit is very poor, this constituting the chief objection to their use. Where steam at atmospheric pressure is necessary for feed-water heating, the inefficiency is of no importance. Their use is determined principally by questions of convenience and economy, it being absolutely necessary to install them for starting purposes.

741. Motor-driven exciters are in use in almost all stations. They are cheap, economical, efficient and reliable, but cannot be used for the complete equipment. They should not be driven by synchronous motors, because short-circuits on the outside system not in themselves sufficient to cause shut-down of the station, are likely to throw the motors out of step, thus shutting down the plant. Induction motors are almost invariably used. A well-balanced exciter plant consists of units driven both by motors and by prime movers. In some cases, motor-driven units are considered as auxiliary to the prime-mover units, and in other cases the motor-driven plant is considered of first importance; the first plan is probably most in favor.

742. The importance of continuous excitation points strongly to **storage batteries** which are frequently installed of sufficient capacity to excite the entire plant for an hour. Danger of a shut-down of the entire plant by failure of the exciters is not considered great enough in all cases to warrant the great expense of a battery. When used, it may either be floated on the excitation busses, or allowed to stand by fully charged.

743. Another method of securing continuous service is being used with considerable success. The exciter generator is arranged to be driven both by motor and prime mover. The motor is provided with a relay which shuts it down if the voltage becomes low. The governor is arranged practically to shut off the steam at normal speed, but after cutting off the motor, the prime mover continues to drive the unit at but slightly reduced speed.

* Reist, H. G. and Eden, T. S. "Method of Determining Temperature of Alternating-current Generators and Motors, and Room Temperature; *Trans.* A. I. E. E., 1913.

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744. The size of the exciter plant depends upon the size of the power plant and the types of generators used. Small, low-speed generators require up to 3 per cent. of their capacity for excitation. Large, high-speed turbo-alternators may require as little as 0.50 per cent. The exact requirements may be obtained from the manufacturer. The total capacity should be ample to carry the whole excitation load with the spare apparatus out of commission. The amount of spare apparatus required is not very definite; practice ranges all the way from depending on the overload capacity to having two to three times the total capacity required.

745. The number and relative size of the exciter units should be chosen for the greatest simplicity and the required flexibility. The minimum size of any unit is in general dictated by the requirements of the largest generator. It is doubtful if the largest exciter should be large enough to excite the entire plant. Except in very large plants a size sufficient for half the equipment, with a total of three units, will give very satisfactory results.

746. The exciter voltages in common use are 125 volts for all except the very largest plants where 250 volts are used. The generators are usually flat compounded. With standard exciters it is possible to run at not more than 15 per cent. over standard voltage, which is quite sufficient to take care of the excitation of ordinary alternators at full-load. Where overload capacities are to be used, it is frequently desirable to raise the excitation voltage as much as 25 per cent. during the peaks. Exciters can usually be arranged for this voltage with very little deviation from standard design.

747. The cost of exciter sets installed, ready to run, exclusive of wiring, piping, etc., could be taken as follows:—Pre War:—1921:

Compound-engine drive,	$1,000 plus $35 per kw.—plus $68 per kw.
Simple-engine drive,	$750 plus $26 per kw.—plus $52 per kw.
Steam-turbine drive,	$425 plus $31 per kw.—plus $60 per kw.
Induction-motor drive,	$625 plus $15 per kw.—plus $30 per kw.

The cost of exciters attached to the shafts of the main generators can best be expressed as a percentage of the cost of these generators; this will vary from 3 per cent. to 5 per cent., depending somewhat on the speed.

748. Exciter wiring systems are in use covering practically all the direct-current types of switchboards. On account of the low voltage no complications need be entered into except as may be necessary to make available the various sources of excitation. Occasionally a double exciter bus is desirable, but in most cases it adds complications without any adequate gain to the service. Alternating-current wiring for motor-driven exciters should be worked out on the basis of the exciters being most important feeders, unless, however, the presence of a storage battery makes this treatment unnecessary. In stations above 2,300 volts, it is recommended that transformers be used in connection with the exciter motors, as small machines wound for high voltage are not sufficiently reliable.

749. Excitation switching appliances. The current must not be broken without at the same time short-circuiting the field windings, otherwise punctured insulation will result. This requirement calls for special field-discharge switches. It also limits the use of circuit-breakers to those operating on reverse current, thus serving to cut out damaged exciters. Fuses of very large overload capacity, which will blow only during most severe trouble, are used for the protection of the exciters.

750. Field rheostats for small generators are usually mounted on the back of the switchboard, but for large machines some more convenient location involving remote control is necessary. Electrically controlled rheostats are frequently necessary in large stations and are operated either by solenoid and ratchets or by motor; the latter is necessary where the field current exceeds 300 amp.

VOLTAGE CONTROL

751. Hand regulation. Voltage is controlled in all systems by hand regulation, whether or not there are automatic means. Hand regulation alone is suitable only where the load is steady and the generators inherently regulate well.

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752. Automatic regulation may be secured by two methods; first, th automatic adjustment of the field resistance by motors or solenoids controlle by a relay; second, the alternate short-circuiting and insertion of resistanc in the field circuits. The first method is used in the **Thury regulato** the second method in the **Tirrill regulator.** The first method makes th adjustment more or less gradually; the second changes the resistance muc more than necessary, alternately one way and then the other, while th time lag of the field windings produces a practically steady voltage of a valu depending upon the proportionate time the resistance is in and out of circuit The latter method is inherently more sensitive than the first and is prac tically the only one in use in America.

753. The Tirrill regulator for small direct-current machine operates as follows (see Fig. 86). The regulation depends on the rapid mak and break of contacts *A* which short-circuit the resistance in the shun field circuit of the generator. The closure of these contacts depends upo the machine voltage across the relay *B*. The contacts closed by this rela serve only to close or open one of the two differential windings on the magne *C*, which in turn operates contacts *A* cutting in or out the field resistanc When the voltage is high, relay *B* opens one winding in *C* which in turn caus the latter to open contact *A*, inserting the resistance, and *vice versa*. Th final result of operation is that the contacts vibrate continuously and remai open or closed a longer or shorter portion of the time as may be require to keep the voltage steady. A regulator of this type with multiple contact at *A* can control machines up to 125 kw.

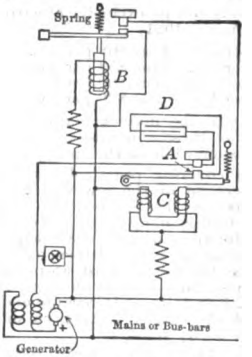


FIG. 86.—Tirrill regulator for small direct-current machines.

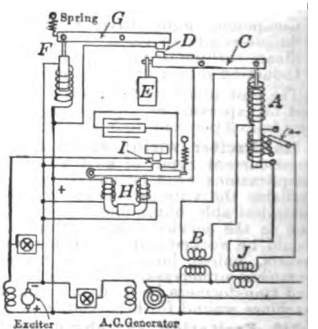


FIG. 87.—Tirrill regulator for large machines.

754. Tirrill regulators for large direct-current machines an alternators operate as follows (Fig. 87): The solenoid *A* is connected acro the bus bars, usually through a potential transformer. The core, which lifted by the solenoid, is attached to the lever *C* on the other end of which a contact *D* and a balancing weight *E*. Across the exciter terminals connected a solenoid *F* whose core is attached to the lever *G* with conta *D* on the other end. This lever is pulled in a direction to close the contact by a spring so designed that the plunger *F* is pulled downward in direc proportion to the voltage. This arrangement gives greater sensitivene than the simple arrangement at *B*, Fig. 86.

When the alternating voltage is low the weight of the plunger *A* overcome that of the balancing weight *E* and closes contact *D*, causing relay *H* to clos contact *I*, thus short-circuiting the field resistance and raising the excite voltage and the alternating voltage. As the exciter voltage rises, solenoi *F* pulls down its plunger and lifts contact *D*, but as long as the alternatin voltage is low, the lower contact follows. When the alternating voltag

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ase above the correct value the contact D is opened, which causes the re-istance to be inserted again in the field circuit. The winding K on the olenoid A allows compounding with the load, which may compensate for he average line drop. In stations where there are several exciters, the relay I operates a number of contacts I_1 one or more for each exciter. In very arge stations a separate regulator is used for each exciter.

756. Regulators with exciter batteries are possible by the use of oosters in the exciter bus under control of the regulator, bucking or boost-ng the voltage supplied to the field windings.

756. Manual regulation with regulators is secured by varying the nistance in the circuit of solenoid A, Fig. 87.

757. Protection against regulator failures or abnormal conditions ould be provided whereby excessively high or low voltage results in the peration of a relay, thereby making the regulator non-operative.

758. Exciters for Tirrill regulators require careful adjustment for arallel operation. Field circuits should permit voltages from 40 per nt. to 140 per cent. normal. They must respond rapidly and equally to ange of resistance. Unequal response causes the quicker machine to take l the load and it may flash over.

759. The cost of Tirrill regulators installed is from \$500 to \$1,500 ch, exclusive of instrument transformers.

760. Feeder regulators for alternating-current circuits consist essentially compensators, the secondary winding of which is in series with the outgoing rcuit. They are fully described in Sec. 6. There are two types, the ntact type and the induction type, the latter being preferable. These gulators may be either single phase or polyphase as necessary. They are ually wound for ± 10 per cent. regulation. They may either be hand op-ated, or automatically operated through a relay and motor to compensate line drop thus maintaining constant voltage at a distant point. The st of 2,200 volt automatic feeder regulators for ± 10 per cent. regulation s about as follows: before the war single phase, \$300 + \$350 per 100 amp. ree phase, \$600 + \$600 per 100 amp. If motor-operated but non-auto-tic, about \$80 is saved. Hand-operated regulators save about \$150. r 1921 costs add 60 per cent.

LOW-TENSION DIRECT-CURRENT SWITCHING

761. Direct-current switching may conveniently be grouped in the owing **general classes:** (*a*) Single polarity; (*b*) Double polarity with ualizer on pedestal; (*c*) Double polarity with equalizer on panel; (*d*) Three e; (*e*) Multiple voltage.

Obviously a great number of subdivisions could be made, the number busses being the most important. Fig. 88 shows the elementary wiring these various classes, leaving out all auxiliary wiring and all instruments.

762. Parallel operation of compound generators is secured by the alizer connections which are usually of one-half to one-third the rated acity. They parallel both terminals of all series fields, making the direc-n of current in all of them necessarily the same. Parallel operation is y discussed in Sec. 8.

763. Single-polarity switchboards find their greatest use in railway rk where the negative bus is at approximately ground potential, and is ally located in the basement beneath the machines; it should be insulated, ever. The circuit breakers and instruments are in the positive side of board and the equalizer and negative switches are on small panels or estals near the machines. The feeders are frequently without negative tches.

764. Three-wire switchboards are used for combined lighting and power tems. The generators require an equalizer on each side. If both these alizers are thrown in, the machines are paralleled as shunt machines, hat some means must be taken to make it possible to close the equalizer tches only at the same time as the main switches. This usually calls for -pole switches on small boards and two double-pole switches on the e, each double-pole switch consisting of one line and one equalizer switch. s obvious that a circuit breaker and instruments are needed in each side. the case of two-wire full voltage feeders, a double-pole circuit breaker ecessary when the neutral is grounded.

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765. The instruments required to measure completely the output o the machines or of a feeder, comprise an ammeter or a wattmeter, or both for each circuit-breaker shown in the diagram (Fig. 88), together with voltmeter on the main bus. For purposes of connecting incoming generator

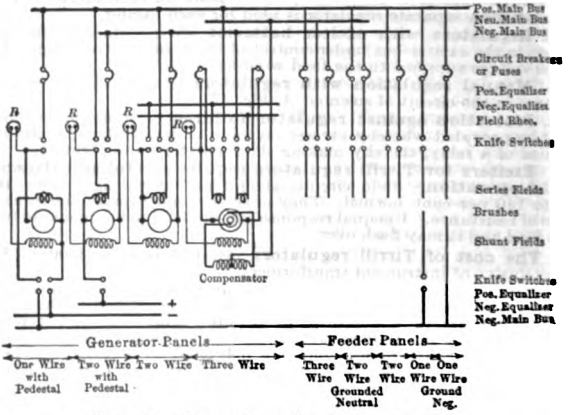


FIG. 88.—Elements of direct-current wiring.

provision must be made for a voltmeter on each machine, or a socket and plu which will enable its voltage to be measured by a common machine vol meter. (Fig. 91.)

766. Double-polarity switchboards find their greatest use in pow work, particularly at 250 volts. The are desirable where both bus bars mu be insulated. Except for large statio there is no disadvantage in having bo polarities on the same board. Exce on small boards, it is desirable to ha the equalizer switches on pedestals ne the machines (Fig. 89).

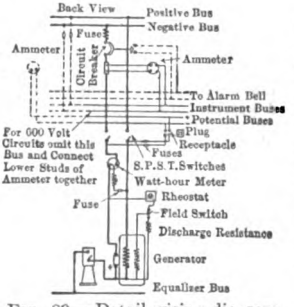


FIG. 89.—Detail wiring diagram of generator panel.

767. Multiple-voltage switchboards are in use where three-wi distribution is extensive. The ext busses are operated at a voltage high than the main busses to take care the drop in long feeders. Their vol age is usually maintained by booster although in some cases provision is ma for connecting the generators to eith set of busses.

768. Double bus bars are seldo warranted except for operating at tw voltages. However, when there a two distinct classes of service whi should be kept independent, doub bus bars are desirable (Fig. 90).

769. Spare circuit breakers are almost necessary in heavy railwa work and provision should be made for inserting them in a simple manne (Fig. 91).

770. Auxiliary circuits are frequently installed to accomplish mar different purposes. Some of the more commonly used are as follow

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(*a*) Voltmeter bus and receptacles to enable the use of one instrument for all machines; (*b*) Current supply for instrument excitation and the operation of circuit breakers; (*c*) Signals indicating open breakers; (*d*) Remote

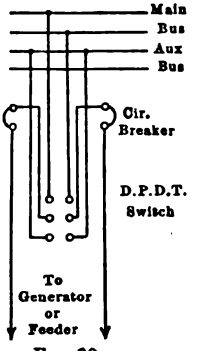


FIG. 90.

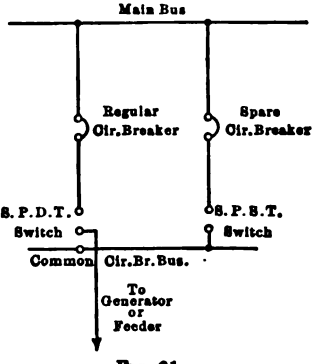


FIG. 91.

FIGS. 90 AND 91.—Wiring for spare busses and for spare circuit breakers.

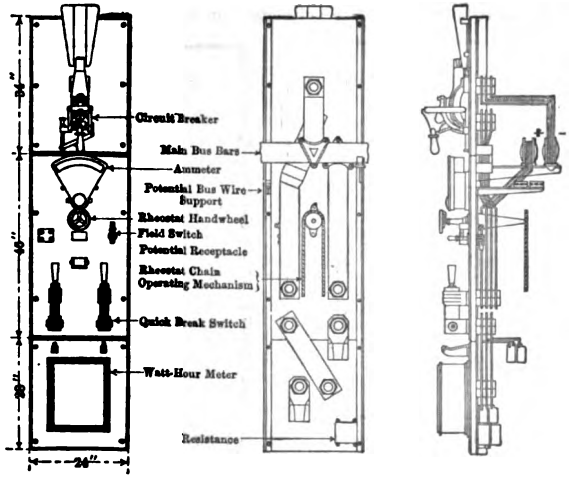


FIG. 92.—Two-pole generator panel 2500*A*, 250 *v*.

control of circuit breakers and switches; (*e*) Interlocking circuits between circuit breakers; (*f*) Reverse-current relay wiring (Fig. 89).

771. Types of switchboard panels. The accompanying illustrations, Figs. 92 and 93, serve to indicate general types of panels. In very small in

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stallations, the generator and feeder switches may be located on the same panel. In moderate sized plants there may be several feeders per panel although generally each generator has its own. In large systems there is sometimes a separate panel for each feeder, but this is necessary only in very special cases, usually two being grouped on each panel. The require

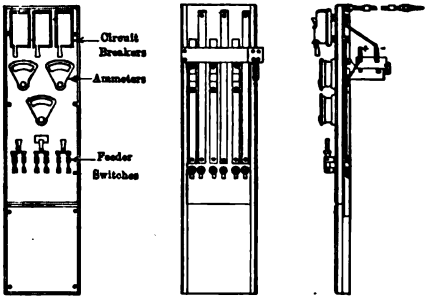


FIG. 93.—Two-wire feeder panels; three small feeders.

ments of ammeters and circuit breakers are the same both for generato and feeder panels except that occasionally two feeders running to the same point are protected with a single set of circuit breakers.

772. **Station panels** are usually provided containing a totalising am meter and watt-hour meter, bus voltmeter (or voltmeters if a three-wir

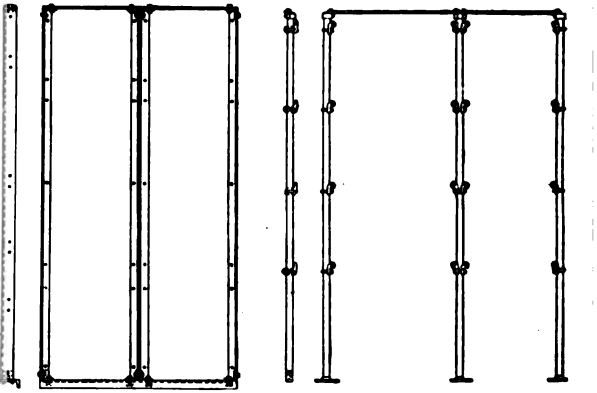


FIG. 94.—Switchboard supports; angle iron and pipe (*Elec. Jour.*, Feb 1913, p. 168).

system), machine voltmeter and switches for auxiliary circuits and power station lighting.

773. **Switchboard supports** are either in the form of angle-iron frame work or 1¼-inch iron pipe (Fig. 94). An inverted channel iron, or sill o hard wood is sunk into the floor to which the upright supports are bolted There is an upright for each joint between panels consisting of two angle

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back to back, or of a single iron pipe. The entire board is braced in an upright position by numerous wall braces. The iron used varies in size from 2 in. × 1.5 in. × 0.25 in. to 3 in. × 2 in. × 0.25 in. One and one-fourth inch pipe is generally used. At least 4 ft. of clearance should be left between the board and the wall to allow for clearing and repairs. In direct-current practice it is customary to insulate the iron framework from ground.

774. Complete lines of detailed fittings are on the market, facilitating almost any conceivable arrangement of framework for supporting the panels and bus bars. (Fig. 95.) Brackets with special insulators are used for the bus bars and longitudinal wires. Vertical small wiring is fastened to the back of the board with small straps. Vertical conductors made of copper bars or heavy wires are usually supported by the studs of the switches and the main bus bars to which they are connected.

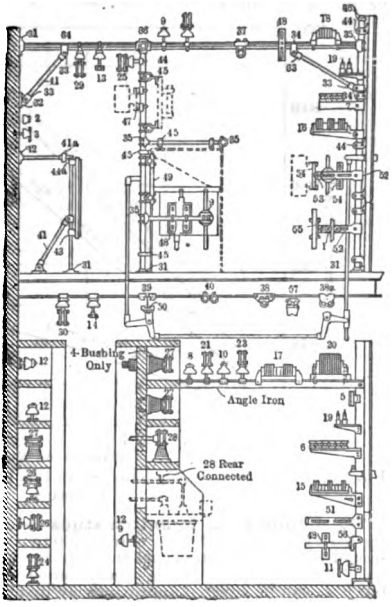


FIG. 95.—Standard switchboard details (Elec. Jour., May, 1913, p. 82).

775. In laying out the wiring for the switchboard panels care should be exercised to have sufficient **clearance** around all live parts (1 in. or more) and to avoid all unnecessary complications. It is important that all panels be as nearly alike as possible.

776. The materials for panels. Marble is used in the more important switchboards on account of its better insulating qualities and better appearance if unpainted; it is advisable if the voltage exceeds 600. Slate is likely to contain conducting veins, but when clear is a perfectly satisfactory material, considerably cheaper than marble and somewhat stronger. Panels from 1.5 in. to 2.5 in. thick are used, depending on the size of the switches and circuit breakers. In some cases even thicker reinforced panels are necessary. Marble panels complete with framework cost from $2.50 to $3 per sq. ft., slate panels from $1.75 to $2.50, on a pre-war basis with 100 per cent. increase to 1921.

777. Bus-bar connections. Bolted joints are preferable in light work, largely on account of the awkwardness of the clamps, but on heavy work, clamps have many advantages. Lap joints or butt joints with covers should be used with a uniform pressure of from 100 to 200 lb. per sq. in. The copper surfaces should be well cleaned. The **current density** in these connections should be from 100 to 200 amp. per sq. in. Under these conditions, the drop in the joint will but slightly exceed that in an equal length of bar.

778. Bus bars are usually made of 0.25-in. or 0.125-in. copper of various widths, seldom more than 10 in. The bars are grouped together with 0.25-in. spaces between them when using 0.25-in. copper and 0.375-in. when using 0.375-in. copper. Aluminium bars 0.25 in. and 0.375 in. thick are sometimes used. Fig. 96 shows approximately the relation between the number

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of bars, the width of the bars, and the **current-carrying capacity** based on a temperature rise of 25 deg. to 30 deg. Cent. Free circulation of air is important and the bars should be supported on edge. Smaller spaces between the bars would greatly reduce their carrying capacity. In general **current densities** of from 800 to 1,000 amp. per sq. in. are not excessive. Where aluminium is used, densities 25 per cent. less should be figured. The **cost** of copper bus bars installed may be estimated on the pre-war basis by adding 10 cents per lb. to the cost of the copper, or 20 cents for 1920.

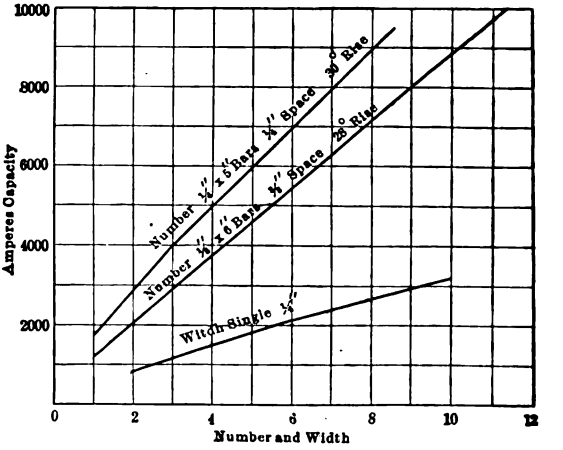


FIG. 96.—Current-carrying capacity of bus bars taken from manufacturer's bulletins.

779. Connections to switch studs between nuts should be figured on the basis of a current density of from 100 to 200 amp. per sq. in. Connections should be carefully fitted and the burr carefully removed from the edges of holes. The cost of making heavy connections between switch studs and bus bars can be covered approximately by adding the cost of 1 ft. of bar for each connection and 6 in. for each joint. For usual panels this work will cost about $10 per panel plus $1.50 per 100 amp. before the war and plus 100 per cent. for 1921.

780. Switches should carry the maximum overload at a temperature rise of not greater than 25 deg. Cent. Current density in the blades and studs ranges from 700 to 1,000 amp. per sq. in. and in the jaws and hinges from 40 amp. to 50 amp. per sq. in. The switches must be carefully made and lined up so that the full contact area is available. If the switch overheats, the contact resistance will be greatly increased by oxidation. A 6,000-amp. single-pole switch is about the **limit of hand operation**. Very large switches with laminated brush contacts closed by toggle joints are sometimes used.

781. Cost per pole of single-throw switches complete with nuts, etc., ready for mounting on switchboards was (on pre-war basis) $1.80 per 100 amp. of capacity; with 40 per cent. added for double throw and 10 per cent. for 600-volt switches, to cover added length of blade and quick-break feature, which should always be used, plus 80 per cent. for 1921 costs.

782. Fuses are the simplest means of automatically opening a circuit under short-circuit or overload conditions. Enclosed fuses are on the market and are approved by the fire underwriters, having capacity up to 600 amp. at 250 volts, or 400 amp. at 600 volts. Up to 30 amp., the contacts are simply ferrules on the end of the tube. On the larger fuses, contact is

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made by blades fitting into jaws similar to those on knife switches. The tube is filled with heat-resisting powder which confines the arc and puts it out quickly. All fuses are supplied with indicators to show when they are blown. They will usually carry full rated load continuously, but will blow in from one to five minutes if the current exceeds 15 per cent. overload.

783. The cost of fuses complete with the clips is about $1 per 100 amp. capacity. The cost of the fuses alone is about 50 cents per 100 amp. capacity, and the cost of **refilling** the fuses is about 20 cents per 100 amp. capacity.

784. Automatic circuit breakers are required on all circuits larger than 400 to 600 amp. and even on the lighter circuits where overloads and short-circuits are likely to be frequent. In order to reduce to a minimum the burning of the circuit breaker contacts, three contacts are successively broken on the opening of a circuit. First the main current-carrying contacts open; then an auxiliary copper contact opens, and lastly a contact opens between the carbon plates and breaks the entire current, thus protecting the current-carrying contacts.

The main contacts in circuit breakers consist almost invariably of laminated copper brush bearing on flat copper blocks, and pressed down by a toggle joint exerting considerable pressure. Several types of breakers are shown in Figs. 97 and 98. The current densities used in the laminated contacts are from 400 to 500 amp. per sq. in. The entire breaker is designed for a temperature rise not to exceed 25 deg. to 30 deg. Cent. in any part.

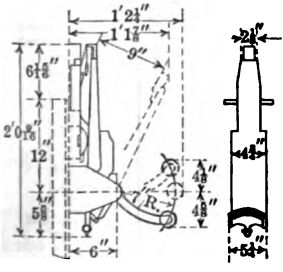


FIG. 97.—Carbon-break circuit breaker 150–2500 amp.

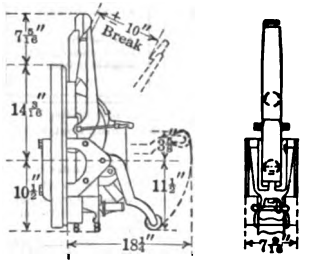


FIG. 98.—Carbon-break circuit breaker 3000–4000 amp.

785. Circuit breakers are ordinarily hand operated by a lever, which is of sufficient power even for the largest sizes (Fig. 98). Frequently, however, **remote control** is desirable and electric or compressed-air operation is used. The **breakers are usually arranged to reopen** immediately without damage when closed on a short circuit. All breakers are supplied with an overload **tripping mechanism** which is adjustable to open the circuit at currents from 60 per cent. to 150 per cent. of rating. Other tripping arrangements may be operated by low voltage, excess voltage, reverse current of a tripping switch located at any convenient point.

786. Multiple-pole circuit breakers are commonly used in the smaller capacities. For many purposes they are specially arranged so that if closed on overload or short-circuit, the tripping coil will release the closing mechanism and the breaker will open before the main contacts are closed. Such breakers may be used on feeder panels, avoiding entirely the use of knife switches.

787. The cost of carbon-break **circuit breakers** is about $32.00 plus $7.00 per 100 amp. of rated capacity per pole; or about 60 per cent. less on a pre-war basis.

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788. Switchboard instruments in direct-current work should be carefully protected from stray fields. Wherever the bus-bar currents exceed 2,000 amp., all except the very best protected instruments will be affected and to secure accurate readings they should be calibrated in place. It is customary to provide instruments with scales such that at the rated load of the machines, the needles will be at approximately mid-point.

789. The cost of switchboard instruments varies between wide limits. Ammeters cost all the way from $15 plus $1.50 per 100 amp. of capacity to $75 plus $2.00 per 100 amp. of capacity. Voltmeters may cost from $20 to $120 depending largely on the type. Watt-hour meters will vary in cost from $35 plus $2.50 per 100 amp. to $200 plus $13.50 per 100 amp. Pre-war costs ran 30 per cent. to 50 per cent. less.

790. Standard switchboard panels embodying the various devices described above and suitable for all classes of work have been developed and catalogued by the various manufacturers, so that it is now possible to buy complete, almost out of stock, panels suitable for almost any kind of work.

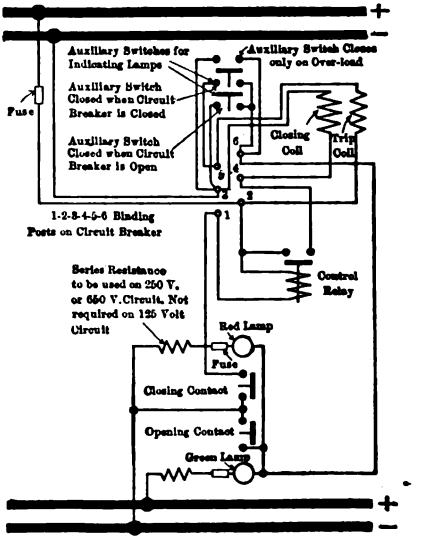


FIG. 100.—Wiring of General Electric solenoid-operated switches and circuit breakers.

Fig. 92, is taken from one of these catalogues. These panels can be purchased for a lower price than it is possible to make up special panels and should be used whenever possible. The particular type shown in this figure cost approximately $100 plus $12 per 100 amp. without watt-hour meter and $220 plus $16 per 100 amp. with watt-hour meter, equipped for 25 volts, on pre-war basis or 75 per cent. more for 1921.

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CONSTANT-CURRENT SERIES SWITCHING

791. Series systems are now used in America solely for street lighting. It is probable that they will continue in use for this purpose indefinitely. The earlier installations used **series-wound generators** operating on the drooping part of the characteristic (Sec. 8). When the total pressure exceeded 2,500 volts, multiple independent armature windings and commutators were used, connected in series externally to the machine. The regulation of these machines is accomplished in two ways, by shunting the series fields or by moving the brushes, or both. Since these machines operate on the drooping part of the characteristic curve, they have considerable inherent regulation in themselves. The adjustments are made automatically by a series-connected relay or operating magnet which actuates

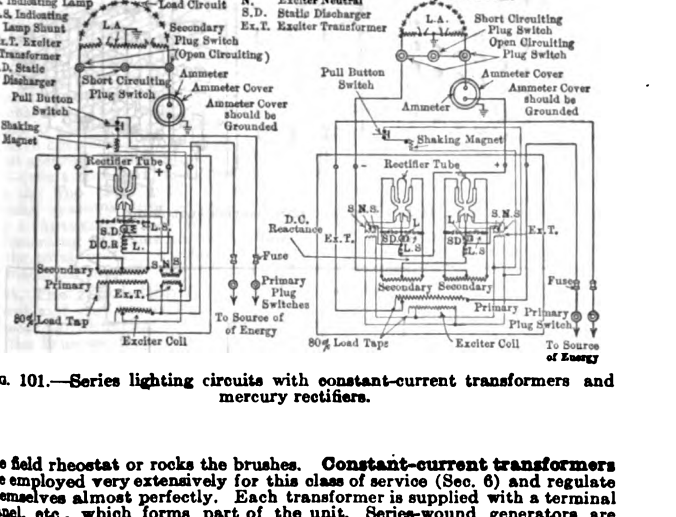


FIG. 101.—Series lighting circuits with constant-current transformers and mercury rectifiers.

the field rheostat or rocks the brushes. **Constant-current transformers** are employed very extensively for this class of service (Sec. 6) and regulate themselves almost perfectly. Each transformer is supplied with a terminal panel, etc., which forms part of the unit. Series-wound generators are installed, however, to a limited extent.

792. Mercury-arc rectifiers are also employed in this class of service, in connection with constant-current transformers, for series direct-curent lighting. The equipment itself is described in Sec. 6. The connections are illustrated in Fig. 101.

793. Switching practice is practically the same whether generators or transformers are used. Since the opening of a series circuit causes full voltage across the break, and short-circuiting causes only a relatively small increase in current, all transfers of circuits are accomplished after short-circuiting the same. Apparatus will run on short-circuit for a short time without damage. The switching is accomplished very simply by means of a transfer or carrier-bus panel as shown in Fig. 102. This arrangement is relatively inexpensive and will allow almost any conceivable switchin-

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794. Ammeters may be connected into any circuit by inserting the proper plug in the sockets in rows 1 or 11. When the plug is inserted the circuit is opened and simultaneously completed through the ammeter. In direct-

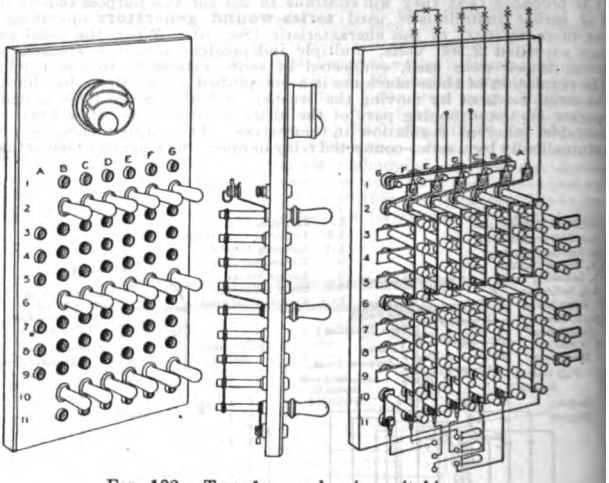


FIG. 102.—Transfer panel-series switching.

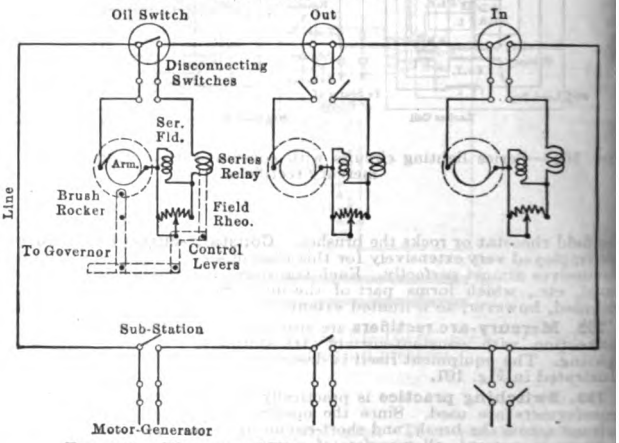


FIG. 103.—Elements of Thury system of transmission.

current work it is necessary to have the instruments in the line circuit They must be insulated for high voltage and the cases protected with th grounded covers to protect the operator. In alternating-current work

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rent (series) transformer may be used in connection with a standard rument.

795. **The Thury system** of direct-current series transmission (Fig. 103) not unlike the series lighting systems in use in this country. Series-und generators are employed, developing up to 4,000 and 5,000 volts each, fficient number being connected in series to secure the desired trans-ion voltage. Currents of various magnitudes are used, approaching amp. maximum. The Thury system, like our lighting systems, is ntially constant-current and is regulated to produce this condition, the tage varying directly with the load. The system is not planned for the eral distribution of energy in small quantities, but rather for transmission ubstations where it is transformed to constant-potential energy. These tations are in series and each has one or more motor-generators with ies-wound motors. This system has not been received with favor in this ntry.

796. **The insulation of the machine windings.** (Thury system) ed not be for the full voltage. If a small number of machines is contem-ated, this insulation could probably be advantageously used, but in large ystems of high voltage and numerous machines, the most economical sults may be expected by insulating each machine from the ground and om other machines. The difficulty lies largely in securing an insulating mpling combining mechanical with dielectric strength. The machines ust each be surrounded by a highly insulated platform so constructed as allow easy access without danger to the operators.

797. **The switching** (Thury system) may be exceedingly simple, as no tomatic circuit-interrupting devices are required or even desired. Since e characteristics of series generators permit short-circuit currents but ghtly in excess of the operating currents, no devices for protecting against cessive currents are necessary. It is probable that satisfactory switching n be secured by hand-operated non-automatic single-pole switches, one to ort-circuit the terminals of the machines and two others to disconnect it om the line (Fig. 103). None of the complications usual in constant-otential systems need be considered. The short-circuiting switch should ve a rupturing capacity equal to the rating of a single generator. The sconnecting switches may be of the ordinary air-break type, but insulated r the total voltage of the system. This insulation is necessary so that e machines may be disconnected from the lines and grounded for repairs.

798. **The regulation** (Thury system) consists in maintaining constant rrent and can be secured in three ways, any combination of which may e used: (*a*) shunting the series fields by an adjustable rheostat; (*b*) rock-g the brushes from the neutral point; (*c*) controlling the speed. The fficulties of commutation prevent any very considerable adjustment by e first two methods, but the generators themselves are self-regulating a large degree. The automatic regulation is secured by a series relay hich operates the field rheostat or other controlling means through direct nnection or by electric control. Large adjustments are taken care of y the starting up or shutting down of machines. Motors are regulated to ve constant speed by centrifugal governors which actuate the field rheostat d rock the brushes. Protective devices are required for short-circuiting e terminals when the voltage exceeds rating.

ALTERNATING-CURRENT SWITCHING

799. **The principles of alternating-current switching** are not cessarily different from those of direct-current (Par. 761 to 790). The me equipment and apparatus may be used for low-voltage work, except r slight modifications to avoid eddy currents. The elements of alternating-rrent switching arrangements are shown somewhat progressively in Fig. 4. The symbols indicate **oil switches**, (*O*) capable of being opened der load and **disconnecting switches** (*X*) incapable of interrupting y except the smallest currents.

The simplest arrangement is that shown in sketch *A* (Fig. 104), where e generators and feeders are grouped at either end of a single bus. etches *B* to *E* indicate arrangements for **sectionalizing the bus** by dis-nnecting switches, which permit the division of the plant at any desired int; some sectionalization by oil switches is frequently desirable. The

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ring bus shown at *E* probably has the greatest advantage. Doub **busses** are shown at *F*, *G* and *H*, which have the added advantage that a group of feeders may be supplied from any group of machines; doub throw disconnecting switches, and double-throw oil switches are shot but the latter are not recommended. The **relay bus** system shown at and *M* gives some control of the sectionalising under load.

The need for increased reliability of switching, as well as increased fl bility has led to the arrangements shown at *I* to *R* inclusive; sketch *I* sh spare oil switches arranged to replace any of the others, through disc necting switches. In the other layouts, there is usually a spare switch each generator or feeder group, so that no equipment need be kept out service on account of switch trouble alone. Obviously, switching arrang ments without limit can be devised to allow almost any conceivable swit ing operation.

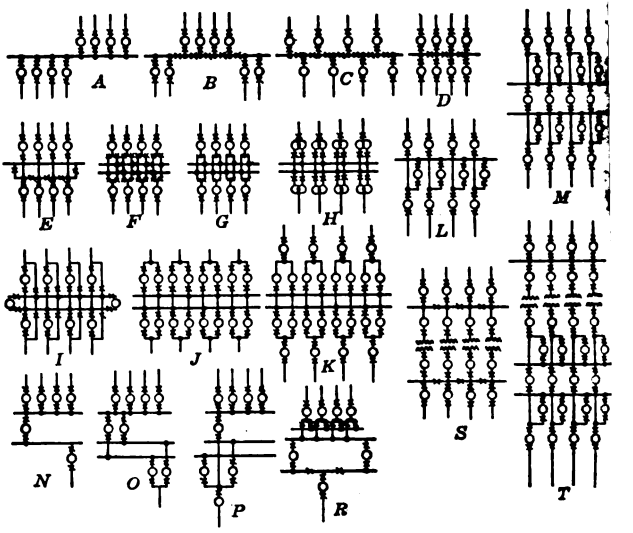


FIG. 104.—Elements of alternating-current switching.

800. Group switching is usually resorted to (Figs. 104*N* and 104 in very large stations of moderate voltage, where the number of feeders relatively large. It facilitates starting after a shut-down, and simplifies t sectionalization of the loads for any purpose. It also provides the maximu of flexibility with a minimum of expensive oil switches.

801. High-tension power stations using transformers require both hig tension and low-tension bus systems. The great expense of high-tens switches and the large space necessary for their enclosure has led to ve simple high-tension layouts. For example, the Ontario Power Compa employs the complicated low-tension layout *M* and the simple high-tens layout *D* (T Fig. 104).

802. The grounded neutral has proved advantageous principal in systems having extensive underground distribution, the object bei to open the circuit breaker of a grounded feeder before a short-circ between phases can occur. A resistance is usually inserted between t

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neutral bus and the ground, of such magnitude that the current flowing to a grounded feeder will comfortably operate its overload relays. When three-phase star-connected generators have a third harmonic in the e.m.f. wave, it will appear as a voltage between neutral and ground. Where dissimilar machines are operated in parallel, a considerable voltage may develop between their neutrals which will make their interconnection dangerous. In such cases it is necessary to introduce resistance in these connections. It is common practice, however, to operate with but a single machine grounded, which prevents interchange of neutral current and still protects the system.

803. Current-limiting reactances are in use on large systems to limit short-circuit currents, thus protecting generators and limiting the duty of the oil switches. These reactances are of the air-core type (Sec. 6. They are used in two ways: those permanently inserted in the circuits, and those inserted only during switching operations. The ordinary turbo-generator will deliver instantaneously on short-circuit, from 30 to 50 times rated full-load current; a reactance sufficient to reduce this to 15 times full-load is apparently all that is necessary in present installations. This reactance may be introduced in the machine leads, in the bus bars, or in the feeders. The first method is commonly used for permanent insertion in very large stations; these reactances are quite large and expensive. The second method is recommended for use between sections of the bus in stations where the switches would otherwise be inadequate. The third method is used for insertion of reactance only during the opening of a short-circuit; there are two switches in series, the first inserting the reactance (normally short-circuited), thus limiting the current to be broken by the second which is mechanically interlocked to open immediately afterward. These reactances are small and may even be included in the oil pots of large switches.

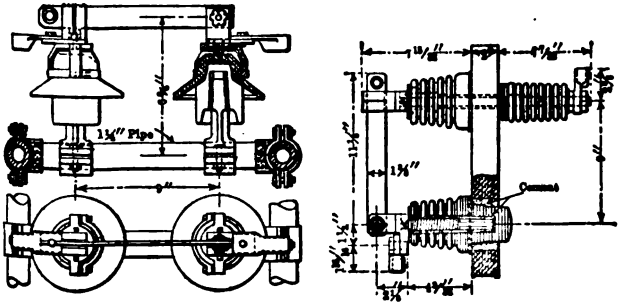


FIG. 105.—Disconnecting switches.

804. Disconnecting switches (Fig. 105) are ordinarily used for sectionalising bus bars or circuits, or for isolating apparatus for grounding or repair, but not for switching under load. They are used sometimes, however, in place of oil switches on one side of parallel transformer banks. Disconnecting switches should not be located to open downward unless locks are provided to keep them from jarring out. In very heavy work care should be used to avoid loops in the wiring which on short-circuits will produce magnetic forces sufficient to open the switch. The cost of 300-amp. disconnecting switches is about $6.00 + $0.80 per 1,000 volts. The cost of 600-amp. disconnecting switches is about $12.00 + $1.00 per 1,000 volts, mounted on metal bases, or 20 per cent. greater than pre-war costs.

805. Expulsion fuses (Fig. 106) are used for connecting potential or small auxiliary transformers to the bus. They are usually arranged also as discon-

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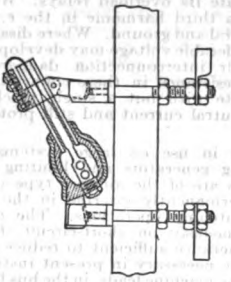


FIG. 106.—Expulsion fuse.

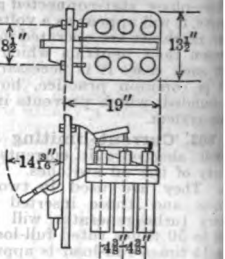
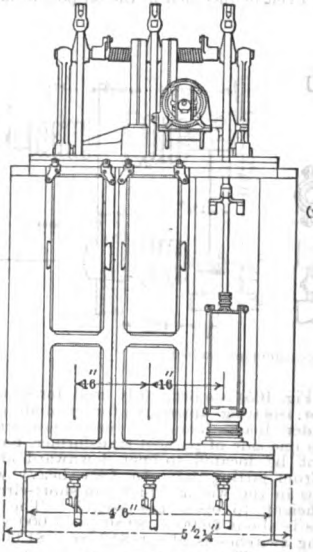


FIG. 107.—Westinghouse type B 300 amp. 15,000 volt oil circuit breaker.



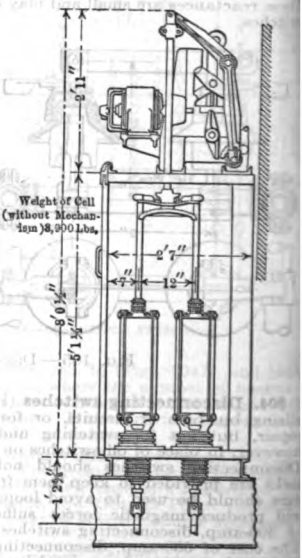


FIG. 108.—General Electric type H-3 oil switch.

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necting switches. They consist essentially of fine fuse wire confined in strong insulating tubes closed at the lower ends. The blowing of the fuse and the resulting confined arc suffice to blow the conducting vapors out of the open end, thus putting out the arc. The tubes are arranged for convenient removal and refilling. They are recommended only in small capacities and moderate voltages, although they are offered up to 60,000 volts, 20 amp. They cost about $20 plus $0.50 per 1,000 volts.

806. Oil circuit breakers are used for interrupting current at all voltages above 600. Three of the numerous types of oil switches are shown in Figs. 107 to 109. The contacts open under oil and the arc is put out by the cooling action, and the pressure of the oil. When a circuit is opened the resulting

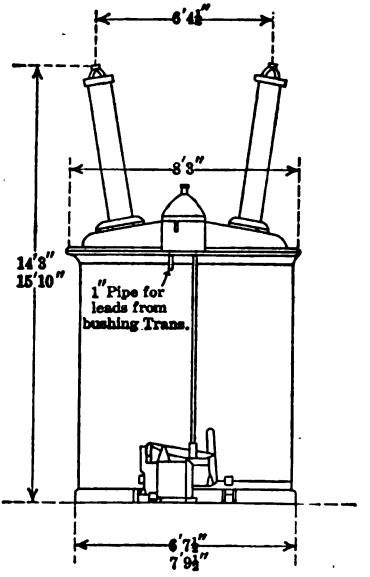


FIG. 109.—Westinghouse type GA oil circuit breaker, 400–600 amp., 135,000–155,000 volts.

arc tends to impart a more or less violent motion to the oil, away from the contacts, but its inertia and pressure due to depth resist the action and quickly quench the arc. This pressure becomes very great in violent short-circuit interruptions, and has been observed as high as 150 lb. per sq. in. a few in. away from the arc. Contacts of various types are used and all have certain advantages; many are arranged with auxiliary contact for the final breaking of the circuit. Most of the breakers are arranged to open by gravity.

A special **circuit-breaker oil** is used which is fluid at low temperatures and is free from moisture. The oil level must be carefully maintained in operation, and the oil must be changed when burned by short circuits.

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807. The temperature rise should never exceed 25 deg. to 30 deg. Cent. in the hottest part at continuous full-load. The **voltage rating** is determined by the insulation distance to the grounded parts and by the breaking distance of the contacts. The Westinghouse Company designs its high-capacity high-voltage breakers, with a ground distance of about 5 in. plus 0.25 in. per 1,000 volts, and with a total breaking distance per pole of about 10 in. plus 0.33 in. per 1,000 volts. Breakers are standard up to 155,000 volts.

The **current rating** is determined largely by the size of the current-carrying parts and may even be in excess of the safe rupturing capacity. Breakers for very high voltage are usually from 300 to 400 amp. capacity, while for 2,500-volt or even 13,000-volt work they are available up to 4,000 amp.

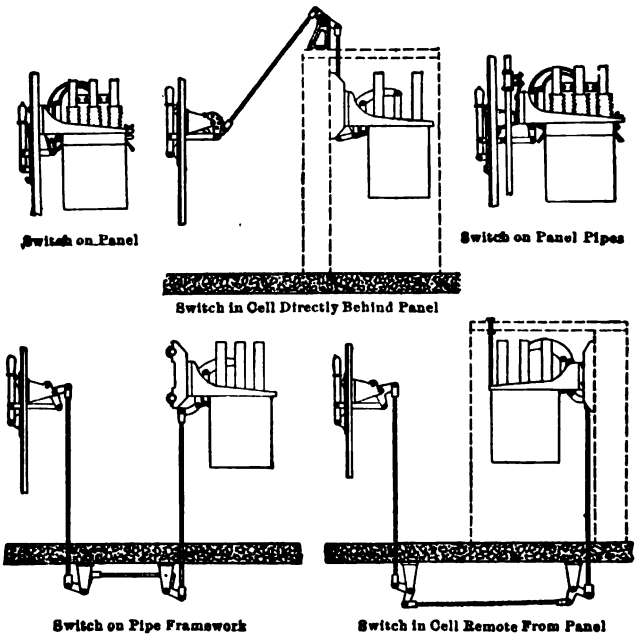


FIG. 110.—Mountings for small oil switches.

808. Oil switches for panel mounting (Fig. 110) usually have their poles enclosed in a common grounded rectangular steel oil-filled tank which is removable by dropping it away from the contacts. This type, when mounted on panels, is not desirable above 2,500 volts and 3,000 kw. station capacity.

809. Wall and framework mounting (Fig. 110) with remote control, using this same type of switch (Par. 810), extends its capacity to about 12,000 kw. at 2,500 volts, or to 6,000 kw. at 15,000 volts.

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Type	Range of current ratings, amperes	Range of voltage ratings, volts	Method of operation	Standard mountings	General uses
General Electric					
P3–6–7–10	2– 200	600–15,000	Hand	Wall	Industrial. Indoors and out.
K5	200– 800	600– 7,500	Hand or Elec.	Panel or Pipe	Industrial and smaller stations.
K12	300–1,200	4,500– 22,000	Hand or Elec.	Pipe or Cell	Distribution and moderate stations.
K25	3,000–5,000	600	Elec.	Pipe	Low voltage high current. Industrial.
K36	400– 600	37,000–155,000	Elec.	Pipe or Floor	Largest transmission and power stations.
H3 and 6	300–4,000	15,000– 70,000	Elec.	Cell	Indoors and out.
Westinghouse					
H and I	5– 100	750– 2,500	Hand	Wall and Panel	Industrial
F1–2–3	5–2,400	750– 15,000	Hand or Elec.	Cell and Pipe	Distribution. Moderate station.
Ba–2–13	300–6,000	750– 25,000	Hand or Elec.	Cell, Panel, Pipe	Moderate to larger stations.
E6–7–8–9	300–2,000	4,500– 25,000	Hand or Elec.	Cell	Indoors.
O and CO	600–4,000	15,000– 25,000	Elec.	Cell	Large stations. Indoors.
G1–2–11	400–1,600	7,500–155,000	Elec.	Pipe	Largest transmission and
GA	400	135,000–155,000	Elec.	Floor	Power stations. Indoors and out.
Condit					
RP	100– 400	3,300– 6,600	Hand	Panel	Industrial.
E3–4	5– 500	2,500– 4,500	Hand	Panel and Pipe	Industrial and smaller stations.
C	100– 300	6,600– 15,000	Hand	Panel and Pipe	Industrial and moderate stations.
D12–13	100–1,200	3,300– 15,000	Hand	Panel and Pipe	Distribution and larger
D15	500	44,000	Hand or Elec.	Pipe and Floor	stations.
Y1–2	1,500–5,500	750– 2,500	Hand or Elec.	Pipe	Low voltage, high current. Industrial.

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811. Remote control. In most cases **electrical control** is used where hand control is undesirable. The operation in most types is secured by solenoids, a powerful one closing the switch, and a lighter one releasing a latch which permits the switch to open by gravity. In the General Electric type *H* switch (Fig. 108) a motor is employed for the purpose of winding a spring which on the release of a stop by a solenoid closes or opens the switch, depending on its position. Following the operation of the switch the motor again winds up the spring. **Pneumatic control** is used in some cases in very high-voltage work. For wiring see Figs. 100 and 111.

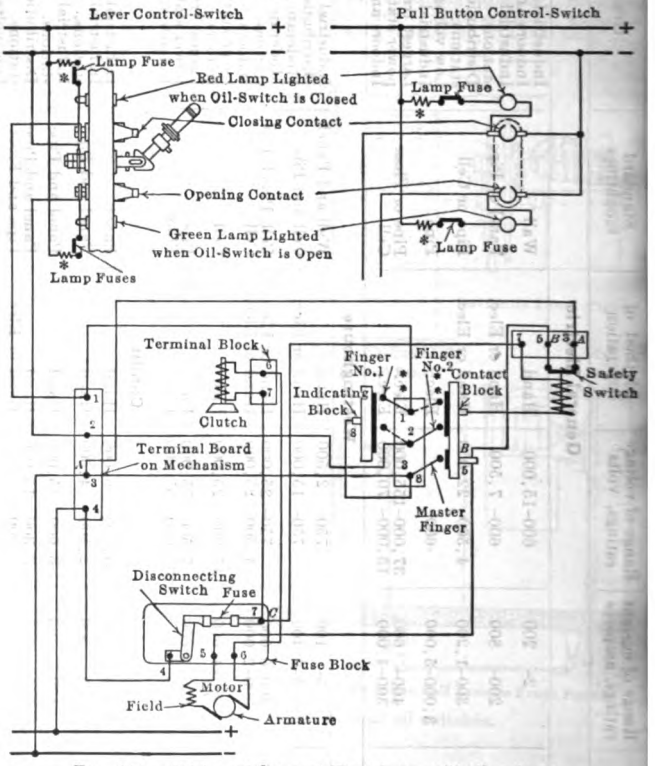


FIG. 111.—Wiring of General Electric type H oil switch.

812. The ultimate breaking capacity of oil circuit-breakers is determined by a great number of variables and the term itself is not very definite. The manufacturers use for this term the maximum size of station in which they recommend the breaker. Obviously this is not the ultimate breaking capacity. A breaker would be safe in a station of low speed units giving low instantaneous short-circuit current, while it might be destroyed in a turbo-generator station of the same size. Important factors determining this rating are voltage, length of break, size and strength of oil tank,

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control of the oil, etc. Generally breakers with a separate tank per pole, or with a separate tank for each contact have larger breaking capacity than those where all the poles and contacts are grouped in one tank. A breaker operated at less than standard voltage will have its ultimate breaking capacity somewhat increased.

813. Hand control of oil switches is used for panel-mounted switches and for remotely mounted switches, in the smaller stations. The remote control is secured through bell cranks and rods (Fig. 110). Where the switches become numerous and are too far away, or the station is of too large capacity, hand operation is undesirable.

814. Oil switches for floor mounting (Fig. 111) have each pole enclosed in a heavy grounded tank and may be supplied with weather-proof entrance bushings and cast-iron covers for the operating mechanism, allowing use out of doors. They are available for voltages from 25,000 to 150,000 and are suitable for stations of almost any size.

815. Methods of Operating Oil Switches*

- **Manual**
  - On panel
  - On wall
  - Remote
    - On flat surface
    - In cell
    - On pipe framework
- **Electrical**
  - D. c. motor
    - Std. sw. op. mechanisms
    - H 3 forms
    - D. c. standard mechanisms
    - A. c. special switches
  - Solenoid
- **Mechanical**
  - Pneumatic
  - Float
  - Pressure reg.
    - Air
    - Liquid

→ Without electric trip or with electric trip

Automatic Control

- **Without series transformers**
  - Series trip
    - Direct relay
    - D. c. trip
    - With or without time
      - Constant
      - Inverse
    - → Overload
  - Auxiliary trip
    - Push button
    - Low voltage
    - With or without shunt transformers or series resistance
- **With series transformers**
  - Depending on load in secondaries
    - Without relay
      - Direct trip
        - a.c.
        - On panel
        - On shaft
      - Without time element
        - Instantaneous
          - Short-circuit, Overload → A. c. trip, D. c. trip
          - Reverse power → D. c. trip
          - Reverse phase → A. c. trip, D. c. trip
          - Differential low voltage under load → D. c. trip
  - Depending on time element
    - With relay
      - With time element
        - Constant or inverse
          - Overload → A. c. trip, D. c. trip
          - Reverse power → D. c. trip

Attachments:
Auxiliary switches (Circuit opening).
Indicating switches (Circuit closing).
Interlocks { Electrical, Mechanical }

* Rushmore, D. B., "Electrical Connections for Power Stations," *Trans.*, A. I. E. E., May 28, 1906.

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816. Switches for cell mounting cover: (*a*) the above type where such mounting increases the safe rupturing capacity about 15 per cent. (*b*) a modification of this type with individual and stronger tanks for each pole, sometimes with separate cells for each pole, which is suitable to 40,000 kw. and 2,500 volts, or even higher with special design; (*c*) switches having two separate round pots per pole each containing a separate contact, and each pole in a separate cell, which are suitable for all capacities, particularly up to 25,000 volts.

817. The source of energy for operating switches should be of utmost reliability. Storage batteries are almost invariably used except in small stations where the exciter system is used. All switching mechanisms should be designed to operate satisfactorily on a range of voltage from 40 per cent. below to 20 per cent. above normal.

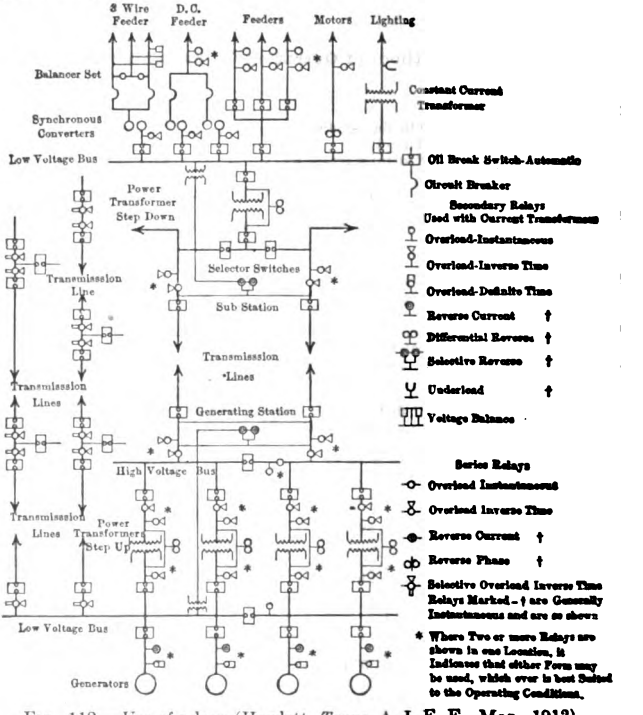


FIG. 112.—Use of relays (Hewlett, *Trans.* A. I. E. E., Mar., 1912).

818. Relays are used operating under all of the conditions outlined in Par. **816**. The most common arrangements are shown in **Fig. 112** (E. M. Hewlett, *Trans.* A. I. E. E., March, 1912). The most common types are: the solenoid with plunger and the meter type very similar to the induction meter. Adjustment for current is made by position of plunger in first type and by strength of spring in second. Adjustment for time is made by bellows or oil pot resisting motion of plunger or disc and magnets resisting turning of

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armature of motor type. Definite time limit is secured by clockwork. Usual adjustments by bellows or magnet give a time in inversely as the actuating force.

It is important that under short circuit conditions relative settings remain unchanged. **The cost of three pole relays** varied from $25 for plain overload instantaneous to $60 for reverse current inverse time limit before the war, with an increase of 75 per cent. for 1921. Some types cost this amount per pole and special types are considerably more expensive.

819. The cost of oil switches varies between exceedingly wide limits, depending largely on rupturing capacity and voltage. Pre-war costs covering three-phase switches were; For small systems up to about 5,000 kw. and 2,500 volts, kw. and 2,500 volts, or 6,000 kw. and 15,000 volts, about $70 plus $10 per 100 amp.; for very large systems of 25,000 volts or lower, roughly $600 plus $20 per 100 amp. hand operation being unavailable. For very high voltage systems there is usually only one current rating for each voltage; such switches for 44,000 volts will cost from $400 for a 15,000-kw. rating to $1,200 for a 50,000-kw. rating; for 110,000 volts, from $1,500 for a 15,000-kw. rating. The cost of electric operation is about $50 additional, exclusive of control wiring. For 1921 costs add 20 per cent for the smaller systems and up to 80 per cent. for the larger.

820. Merts-Price System of relay protection depends on unequal currents at two ends of conductor in trouble. The series transformers at the two ends are interconnected so that, normally, no current flows through the relay. Unbalance due to trouble cuts out the apparatus (Fig. 113).

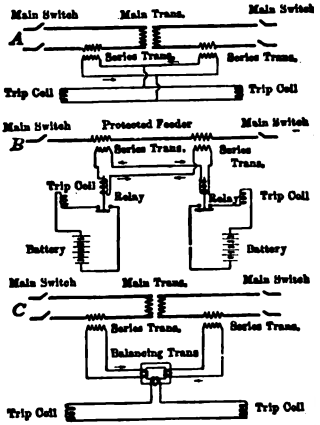


FIG. 113.—Merts-Price systems of protecting transformers and cables.

821. Instrument equipment for generator panels includes:

(*a*) One alternating-current ammeter (where phases are likely to be unbalanced an ammeter is often supplied for each independent phase, or current transformers and transfer switches for connecting the single ammeter to any phase; (*b*) one alternating-current voltmenter (or voltmeter receptacle and plug to connect to common voltmeter); (*c*) one direct-current field ammeter (optional); (*d*) one indicating wattmeter (needed for parallel operation); (*e*) one power-factor meter (or wattless kv-a. indicator, optional); (*f*) one frequency meter (optional); (*g*) one ground detector (not common); (*h*) one watt-hour meter (optional but desirable); (*i*) one synchronising outfit; (*j*) current (series) and potential (shunt) transformers; (*k*) one automatic relay (optional).

822. Instrument equipment for feeder panels includes:

(*a*) One alternating-current ammeter (ammeter transfer switches may be used if phases are unbalanced); (*b*) one indicating watt meter (optional); (*c*) one automatic relay; (*d*) current (series) transformers.

823. Instrument equipment for station panel includes:

(*a*) Synchroniser (extra one optional); (*b*) voltmeters for each phase of each bus (optional); (*c*) frequency meter; (*d*) voltage regulator (optional); (*e*) totalising wattmeter (optional); (*f*) totalizing watt-hour meter (optional).

824. The cost of high-grade switchboard instruments mounted with panel wiring, exclusive of instrument transformers, was before the war as follows: ammeters $40, voltmeter $45, single-phase wattmeters $50, polyphase wattmeters $70, single-phase watt-hour meters $70, polyphase watt-hour meters $125. Large variations in price however exist between various types and grades, but may be taken at 50 per cent. increase for 1921.

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825. The synchronising equipment in a station must be ample enough to prevent any possibility of failure, and should be in duplicate in all except small stations; there should also be synchronising lamps in case of failure of the instruments. There should be more than one set of instrument transformers available for the bus voltage. Synchronizer wiring should preferably be as simple as possible (Fig. 114).

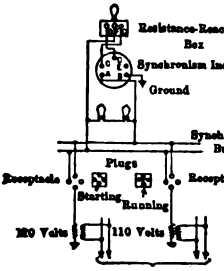
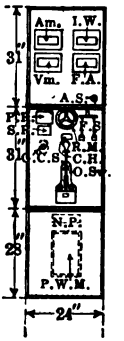


FIG. 114.—Synchronizer wiring using shunt transformers.

826. Instrument transformers (Sec 6, and Sec. 3) are generally used whenever the currents exceed 100 amp. or the voltage 600. They are designed for 5 amp. and 110-volt secondary. Separate transformers of ample capacity should be provided for relays and for instruments. Potential (shunt) transformers are usually oil insulated for all voltages above 4,000 and current (series) transformers for voltages above 15,000. Instrument transformer wiring must be grounded thoroughly, both at the transformer and at the board, to prevent high potential on the panels in case of burnouts.

827. The cost of high-grade instrument transformers was about as follows: on a pre-war basis with up to 80 per cent. increase for 1921.

Series type, 2,500 volts, $10+ $0.60 per 100 amp.; 11,000 volts, $30+ $ per 100 amp.; 33,000 volts, $60+ $18.00 per 100 amp.; 66,000 volts, $175+ $35 per 100 amp.; shunt type, 200-watt size, $20+ $8 per 1,000 volts.



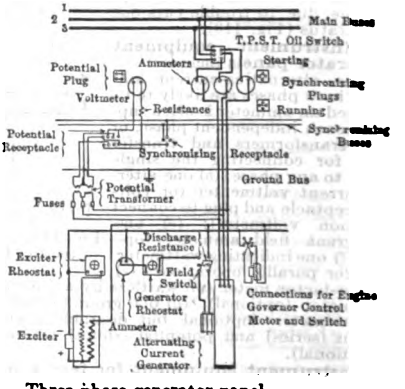


FIG. 115.—Three-phase generator panel.

828. Types of switchboards using the apparatus above described may be divided into three classes:

1. Self-contained panel type.
2. Remote mechanically operated: (*a*) panel boards; (*b*) bench boards.
3. Electrically operated: (*a*) panel boards; (*b*) bench boards.

The capacity and voltage of the station largely determine the type as discussed under oil switches, type 1 being suitable for the smallest and type 3 for the largest systems. Space requirements for the different types are not materially different. Typical panels are shown in Figs. 11 to 118.

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829. Relative costs of switchboards are approximately 100 per cent. for type 1, 120 per cent. for type 2 and 140 per cent. for type 3 (Par. 828). These figures are approximate only for the same electrical layout, whereas different layouts would undoubtedly be used for the stations for which each type would be suitable. The following table gives the costs of typical panels shown in Figs. 119 to 121.

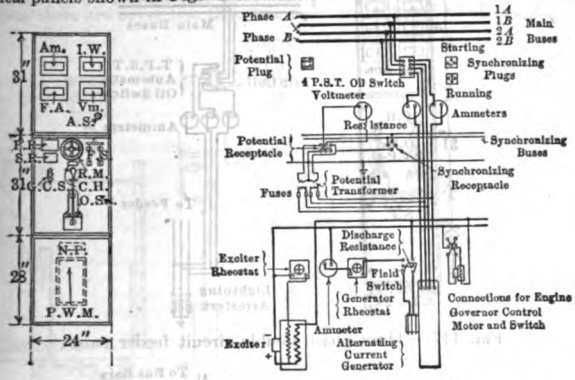


FIG. 116.—Quarter-phase generator panel.

830. Approximate Cost of Switchboard Panels**
C. H. Sanderson, *Elec. Jour.*, 1913.

Kind of panel	Volts	Amps.	Fig.	Cost	U.B.C.*
Generator	2,200	"	120	440	9,200
	6,600	"		385	7,800
Feeder	2,200	"	120	345	9,200
	6,600	"		350	7,800
Generator	2,200	"	119	360	9,200
	6,600	"		310	7,800
Feeder	2,200	"	119	260	9,200
	6,600	"		265	7,800
Generator	11,000	"	121	1,240	12,500
	6,600	"		1,130	15,500
Feeder	11,000	"	121	1,045	12,500
	6,000	"		940	15,500

831. Cost of switchboards. Switchboards on pre-war basis cost from $2 to $8 per kw. of capacity including all wiring and apparatus installed: add 80 per cent. for 1921 costs.

832. Mimic or miniature bus bars are invariably installed on the faces of the control boards in large stations. They represent by single bars exactly the electrical relation of the main switch controlled by each control switch and thus greatly simplify the operation.

833. Grouping of panels. It is customary to arrange the panels as follows, beginning at one end; voltage regulator, exciters, station auxiliaries, generators, feeders, with blank panels sufficient to care for any reasonable extension of the plant. With remote control, particularly electrical, this

* U. B. C. = Ultimate breaking capacity of circuit breakers set for instantaneous trip. Costs include all apparatus necessary and all structures shown but no wiring. Add 10 to 20 per cent. to cover installation.

**Add 80 per cent. for Estimated 1920 Costs.

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arrangement of the switches themselves may be impossible on account o desired electrical layout, but the panels may be so arranged to advantage Remote-control bus structures and switches should be located where ther is room for considerable extension.

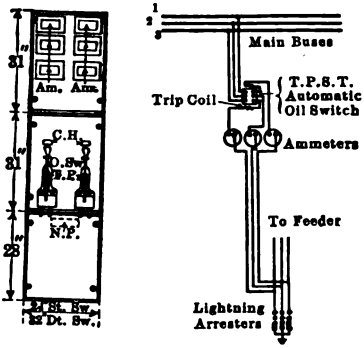


FIG. 117.—Three-phase double circuit feeder pane .

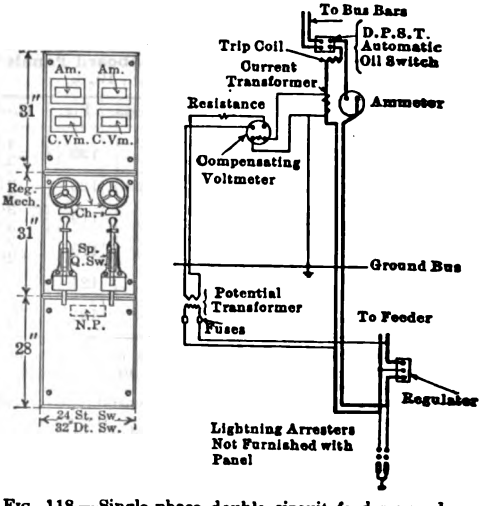


FIG. 118.—Single-phase double circuit feeder panel.

834. **The operation and care of switchboards.** Small stations up to say 5,000 kw. do not need any special operators for the switchboard. The engineer on watch has ample time to take care of any switching operations. With larger stations special operators become necessary; up to 10,000 kw. one

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operator on a watch is enough and, during the light load periods, if the arrangement of the board with respect to the turbine room is suitable, this operator may be unnecessary. Above 10,000 kw. an operator continuously on watch is necessary and frequently an additional man to take care of disconnecting switches and the cleaning and repair of oil switches. Above 20,000 kw. it is customary to have additional men until in the very large stations, there are never less than two men on the board at all times.

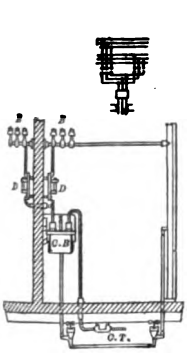


FIG. 119.

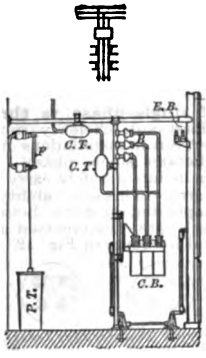


FIG. 120.

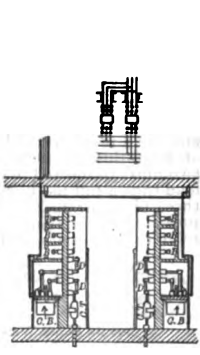


FIG. 121.

835. Bench boards are used only in large stations where the number of circuits is very large. A great saving in space is possible because the instruments do not crowd the control switches, thus allowing two or more generators to be handled on a single panel. Some of the types are shown in Fig. 122.

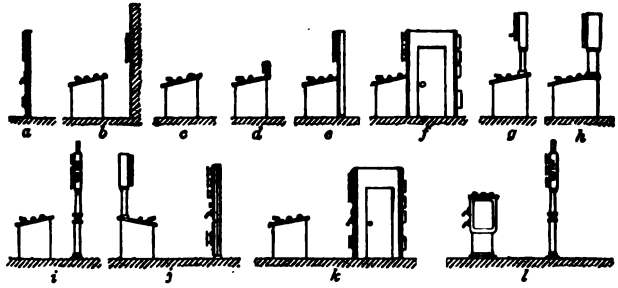


FIG. 122.—Types of bench boards.

836. Load dispatching in some form is necessary on complicated systems. The load dispatcher has full control over and knowledge at all times of the condition of the system. He usually has a map of the system indicating the condition of all electrical apparatus and issues all orders by telephone for the putting on or taking off of any machine or cable. Emergency conditions require a certain suspension of the direct control of the dispatcher, but in such cases a carefully worked out routine must be followed. Some very large systems have no man formally called a dispatcher but in such cases the senior operator in the largest station is given final authority and his orders must be obeyed.

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STATION TRANSFORMER INSTALLATIONS

837. Transformers of practically all types are used for high-tension power-station work. On account of the size and voltage of most stations of this kind, the main power transformers are usually oil insulated, with or without water cooling, and of the shell type of construction. See Sec. 6

838. Air-blast transformers are rarely used above 15,000 volts and in sizes above 1000 kv-a. They are available, however, up to 33,000 volts and 2,500 kv-a. These extremes should be avoided on account of insulation and cooling difficulty.

839. Self-cooled transformers are built in sizes up to about 8,000 kv-a. but the space required is large on account of the necessity of outside cooling tubes or radiators. Up to 1,000 kv-a. corrugated tanks give satisfactory results.

840. The question of single-phase vs three-phase transformers is not definitely settled. First cost, efficiency, simplicity of wiring and floor space, all point to the latter, but in installations of few units the desirability of flexibility frequently dictates single phase. When operated in delta, two units connected in open delta will safely carry about 60 per cent. of the load that a full bank will carry. This same ability also exists in shell type three-phase transformers operated in delta, both primary and secondary, provided the damaged coils are disconnected and short-circuited. The relative floor space occupied is shown in Fig. 123.

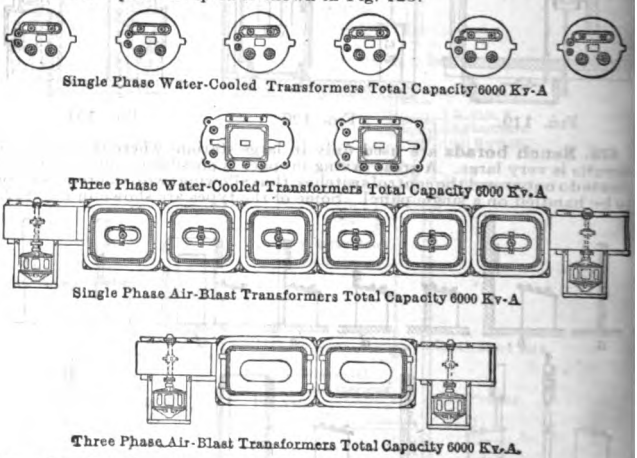


FIG. 123.—Relative floor space of single-phase and of three-phase transformers (G.E. Bulletins).

841. Water cooling is most generally used in large installations. The water supply must be continuous and pure. Where cooling water must be purchased cooling towers can be used to advantage. It is desirable to have negative pressure in the cooling pipes to prevent leakage into the oil.

842. The amount of water required is approximately 4 gal. per min. per 1,000 kv-a. capacity. This amount is not rigid. In winter considerably less is necessary, and in summer fully twice as much can be used to advantage.

843. The cost of water-cooling systems is from 15 cents to 50 cents per kv-a., depending on the source of supply, or approximately 100 per cent. above pre-war costs.

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844. Air-cooling requires blowers taking about 0.25 per cent. of the output. They are usually electrically driven and require from 3 cu. ft. per min. to 5 cu. ft. per min. per kv-a. at pressures from 1 oz. per sq. in. to 0.5 oz. per sq. in., depending on size. The first figures are for 100 kv-a. size and the latter for 1,000 kv-a. size.

845. Oil-insulated transformers are in reliable service up to 150,000 volts and 14,000 kv-a. and down to very small sizes at 25,000 volts. They are the most satisfactory in the average central station.

846. Forced oil cooling can be used for all sizes and gives satisfactory results. The transformers usually have plain boiler iron shells. The oil is pumped in at the bottom and overflows at the top, passing through glass sight tubes to cooling coils located where good air circulation or cooling water is available. This method avoids the possibility of water leaking into the oil through defective tubes, as the oil may be kept under slight pressure. It also allows the convenient drawing of the shells without special piping. The chief objection is that a fire may put the entire equipment out of service. The cost is from 45 cents to 90 cents per kv-a. of capacity, which is considerably higher than water cooling, but there is a considerable saving in the cost of the transformers due to absence of cooling coils.

847. Fire danger from transformers, while not negligible, has been greatly exaggerated in the past. In some installations each bank has been placed in a well-drained fire-proof chamber, in addition to being equipped with a piping system to enable the rapid emptying of the shells into a buried tank. Some of the latest and very important installations have been constructed with simple barriers between banks opening into a common passage. The drainage system is still important but is used principally to facilitate repairs, inspection and the treating of the oil.

848. Convenient handling of the transformers should be provided for either by an overhead travelling crane, or by mounting on trucks on which they may be moved to an inspection pit.

849. Transformer oil must be kept particularly free from moisture; one part in 10,000 will reduce the dielectric strength 50 per cent. Drying outfits, which dry the oil by forcing it through successive sheets of blotting paper, were available before the war at from $500 to $1,000 with capacities of from 5 to 20 gal. per min. For 1921 costs add 80 per cent.

LIGHTNING ARRESTERS

850. Lightning protective apparatus is used in power stations to protect the apparatus therein from abnormal potentials on the system, whether caused by lightning disturbances or by switching operations. The ideal apparatus will immediately relieve the system of excess voltages, allowing no flow of the dynamic current of the system, and be ready for immediate service again.

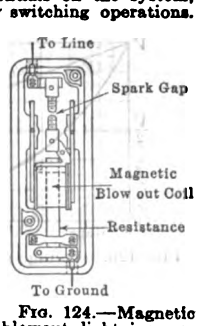


FIG. 124.—Magnetic blowout lightning arrester for low voltage.

851. The magnetic blow-out principle is frequently employed, particularly in low-voltage arresters. The spark gap is placed between the poles of an electromagnet (Fig. 124) excited by the flow of current which immediately bows out the arc. Series resistances are usually employed with this arrangement.

852. Choke coils are simple open air core reactors inserted between the arresters and the apparatus to be protected to choke back the lightning disturbances, which are of very high frequency, thus allowing the arrester to discharge with a minimum strain on the station apparatus. To secure the full benefit of the choke coils, the connections to the arresters should be as straight as possible.

853. Spark gaps are used in practically all types of arresters, set at sufficient distance to prevent sparking over at ordinary voltages. Obviously something additional is needed to limit the flow of dynamic current after relieving the excess potential. Their most common use without considerable modification is to protect transformer secondaries, a single gap per bank of transformers being used.

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854. Series resistances are usually inserted between simple spark gaps and ground for the purpose of arresting the current. This is accomplished, however, at a sacrifice in efficiency of the arrester in removing the disturbances which frequently have considerable current volume. This method is used, however, in many types from the lowest to the highest voltage.

855. Fuses inserted in series with a gap (Fig. 125) are not uncommon. They serve to relieve the system and interrupt the current, but they have the serious disadvantage of being able to handle only a single discharge. A simple circuit breaker is sometimes similarly used on low-voltage systems.

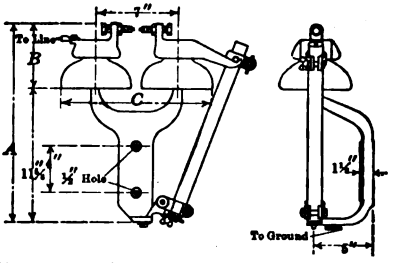


FIG. 125.—Air gap lightning arrester with fuse.

All of the above arrangements have their simplicity to recommend them but they are inadequate on all but very small or low-voltage systems.

856. Horn gaps are modified spark gaps which consist of conductors arranged in a "V" with a suitable gap at the bottom. The flaring sides are shaped so that the arc in rising by the heated air is lengthened and finally blown out. Careful proportioning is necessary, but even then the horns will fail to put out the arc from a heavy current.

857. Multigaps, which consist of a large number of gaps in series, between relatively large cylinders of non-arcing (composition) metal, have many advantages. When placed between line and ground the potential drop between gaps is much greater near the line than near the ground, due to the electrostatic capacity of the cylinders (Fig. 126). This makes possible a much greater aggregate gap distance than with a single gap, which greatly aids the quenching of the dynamic arc. Lightning disturbances, being of high frequency, cause a still greater potential gradient, which will allow the disturbances to pass at a relatively low excess voltage. As soon as the gaps break down the flow of current causes an equal drop in all gaps.

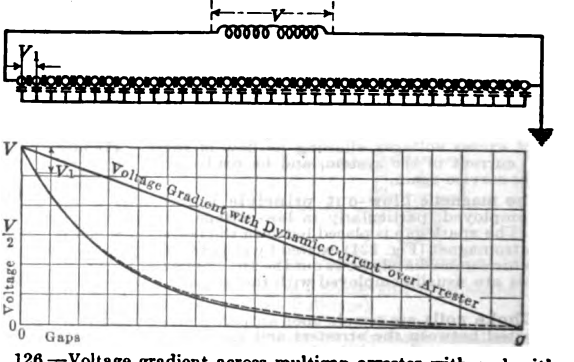


FIG. 126.—Voltage gradient across multigap arrester with and without dynamic current.

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The non-arcing metal has a low boiling point and acts as a rectifier, not allowing the dynamic arc to be resumed on reversal of current, if the voltage is kept low enough. The greater the number of gaps in series the more definite this action.

858. Multipath arresters allow high voltages to discharge along the surface of a very high resistance rod in numerous very fine sparks, the normal voltage being unable to continue the arc. This type is limited to small discharges.

859. Graded shunt resistance combined with multigaps, allows a greatly increased effective number. Referring to Fig. 127, which shows the arrangement used by the General Electric Co., the full line voltage is normally across the lower group of gaps, the resistance being low enough to accomplish this result. When breaking down, the flow of current through the high resistance causes a

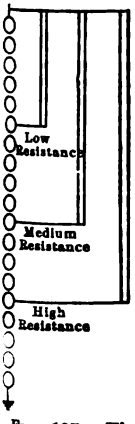


Fig. 127.—Elements of graded shunt multigap arrester.

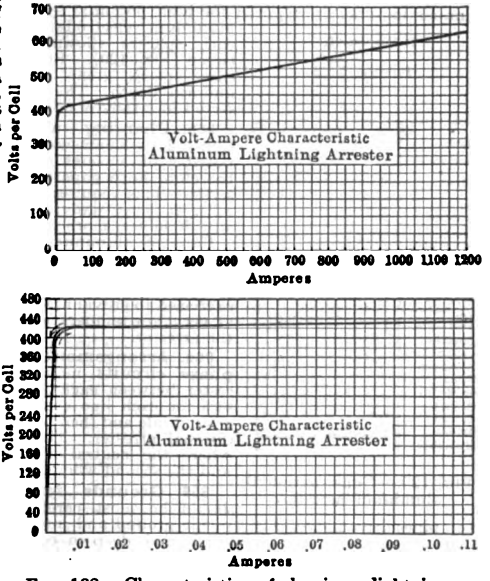


Fig. 128.—Characteristics of aluminum lightning arrester.

voltage across the second lower group of gaps which, if the lightning discharge is heavy enough, are broken down, thus inserting additional gaps to quench the arc. Similarly if the arc continues due to the discharge being too heavy, additional gaps are inserted until the entire group is in series. If this number will not rupture the arc the arrester may be destroyed, this being the limitation of the apparatus.

860. Series-resistance multigap arresters are built by the Westinghouse Company in recognition of this condition, called "Low-equivalent arresters." The series resistance is expected to limit the rate of discharge within safe limits. This type ordinarily uses but a single shunt resistance. There is considerable difference of opinion as to whether or not this series resistance is desirable. It sometimes saves the arrester, but at the expense of the apparatus by increasing the time necessary to relieve the system.

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861. Care of multigap arresters requires the frequent removal of dust best accomplished by blowing with compressed air. The arresters shoul be disconnected during this process.

862. Aluminum-cell lightning arresters depend for their action on th properties of aluminum when inserted in a suitable electrolyte, shown b Fig. 128. When an e.m.f. is applied between two electrodes, insulatin films are formed which break down if the forming voltage is exceede and reform immediately when the voltage becomes normal. This ce more nearly conforms to the ideal than any other arrester; it may be se for a very small increase in e.m.f.; its discharge rate is enormous and i immediately resumes normal condition after the discharge. Since the cel can be formed to withstand permanently only about 300 volts, a gre number in series is required for high potential systems. Conical shape aluminum electrodes are mounted on ro with spacers allowing a uniform space b tween (Fig. 129). Electrolyte is inserted i these spaces, great care being required to g uniform depth. The whole stack is then i serted in a tank of oil.

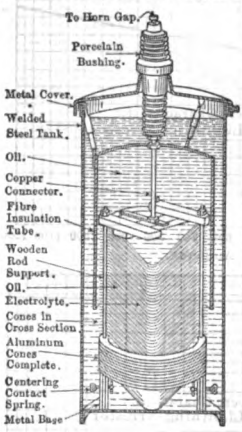


FIG. 129.—Construction of aluminum arrester.

863. Charging aluminum arreste Continuous connection to the line is n possible on account of the loss of energy, an therefore horn gaps are usually connected i series. This requires frequent charging of t cells, at least daily, because the film grad ally dissolves, more rapidly in warm weathe

Care of aluminum arresters requires n only this frequent charging, but also watchi the charging current which is a guide to th condition of the electrolyte. Care should b exercised to prevent freezing of the electroly at very low temperatures, as it might destro the arrester.

864. Arrangement of arresters on poly phase circuits may consist either of an a rester between each line and ground, or arre ters for each line connected together on t ground side and then to ground through an a ditional arrester. The first method is us where the neutral of the system is ground and the second where ungrounded.

865. Grounds for lighting arreste should be most carefully made. Numero iron pipes driven several feet in the ground and interconnected by a copp strip are good. Copper plates buried deep in coke with earth filling a also used. In addition the arrester ground should be connected to the ste frame, piping, and other grounded materials in the building.

866. Summary of uses of various types of arresters.

(1) Spark gap—
- (a) Series resistance } D.C. systems, all voltages.
- (b) Fuse } A.C. trolleys, along the line.
- (c) Magnetic blowout
- (d) Plain—Single point on transformer secondaries.

(2) Horn gap—
- (a) Series resistance } A.C. systems, all voltages, locate on poles.
- (b) Fuse } D.C. and A.C. series systems.

(3) Multipath—Frequent location along D.C. lines.

(4) Multigap—A.C. systems.
- (a) Plain—Frequent location along small distribution systems.
- (b) Series resistance—Frequent location along systems up 15,000 volt
- (c) Shunt resistance } Station use on systems of modera
- (d) Shunt and series resistance, } size and length of line.

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(5) Aluminum cell—
(a) In small jars or tanks, } D.C. systems along the line and D.C. stations.
(b) All stacks in one tank, A.C. systems up to 7,500 volts.
(c) Separate tanks, A.C. system up to 150,000 volts.

867. The cost of lightning arrester equipment was on pre-war basis, (or 100 per cent. higher for 1921). Three-phase grounded-neutral systems: Aluminum cell, $70 + $10 per 1,000 volts; multigap type, $13 per 1,000 volts. Three-phase ungrounded: Aluminum cell, $100 + $15 per 1,000 volts; multigap type, $15 per 1,000 volts.

868. The cost of 200-amp. choke coils of the "hour glass" type, was before the war about: $20 + $0.50 per 1,000 volts, up to 70,000 volts; $30 + $0.80 per 1,000 volts, above 70,000 volts; the increased cost per 100 amp. is about $7. Pancake-type coke coils cost about $12 + $20 per 100 amp. for 2,500-volt service and $40 + $40 per 100 amp. for 25,000-volt service. Add 65 per cent. to estimates for 1921 costs. The cost of installation of the above can usually be covered by a 15 per cent. increase, in addition to freight.

POWER STATION WIRING

869. Bus bars are made either of copper as discussed in Par. 778 of this section, or, in the case of high-potential stations or moderate potential in small sizes, of copper tubing, copper rods, and sometimes brass or iron pipe. Special bends and fittings are available for this pipe work. Where the current capacity is small, the physical stiffness required dictates the size of conductor. Bus bars are seldom continuously insulated. They are usually supported in the open in small low-voltage stations, and in all stations of very high voltage. Cell structures are used in stations of moderate voltage in all except relatively small stations.

870. Switch wiring on the board, or on the switch structure, should be stiff and well insulated for the full voltage, because the wires are particularly near together at this point. Stranded wires are seldom used except for simple layouts where accurate alignment is not necessary.

871. Main generator and exciter wiring should be run by the shortest possible route and provided with ample insulation, even above ordinary requirements. This wiring is not protected by automatic switches. Multiconductor cables are not recommended and alternating-current and direct-current wiring must not occupy the same duct.

872. Instrument and control wiring form practically the nervous system of the power plant. Great care must be used to avoid trouble and only the highest grade of insulation should be used. Iron conduit should be used for all of the wires, terminating as closely as possible to the instrument panels and to the transformers. Terminals at oil switches and instrument transformers should be most carefully protected to prevent high-tension current from reaching them during switch troubles. All instrument wiring except that in main circuit must be thoroughly grounded both at the instrument transformer and at the panel. Terminal boards on the panels are of great assistance in calibrating instruments. Alternating-current and direct-current wires should not be run together any more than can be avoided.

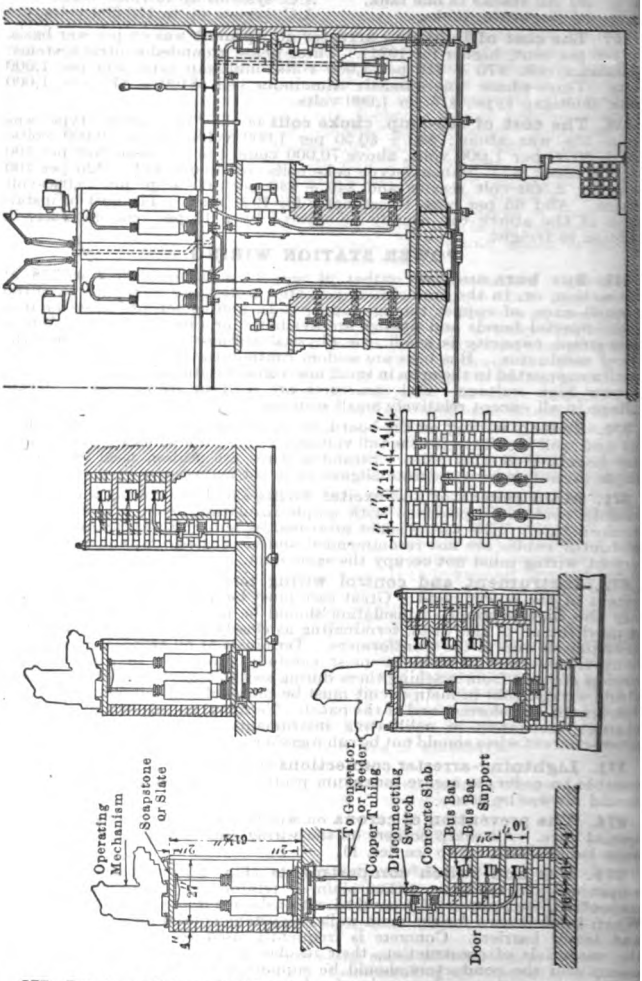
873. Lightning-arrester connections should be as simple and direct as possible in order to secure maximum protection. Disconnecting switches should always be used.

874. The prevention of corona on wiring of very high tension requires special care. All sharp corners on the wiring and the switching apparatus must be avoided. Also see Sec. 11.

875. Bus and switch compartments (Fig. 130) are made of brick, soapstone and concrete, either plain or reinforced. Openings for switch inspection, etc., are usually covered with asbestos doors conveniently hung. When brick is used for the main walls, soapstone is used for horizontal walls and lesser barriers. Concrete is frequently used throughout. Whatever the materials of construction, their insulating qualities are not depended upon, and the conductors should be supported on insulators designed for full voltage with a wide margin of safety. Wide differences in design are possible, as is indicated in the cuts, and it is seldom that the same arrangement is used in two stations.

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876. The cost of bus and switch structures varied widely, fro
$50 per switch in small sizes to $300 per switch in large capacity switches f
15,000 volts on pre-war basis or $90 to $600 for 1921.



877. Ducts and iron conduits are largely used in power station wirin
but the latter should be avoided for alternating-current work of more tha

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very moderate current capacity. Clay or fibre ducts laid in concrete in the floor, or built into the ceiling cost, from 20 to 50 cents per duct ft. before the war and 110 per cent. higher in 1921. Iron conduit supported by clamps costs, in place, from 12 cents per ft. for the ½-in., to $1 per ft. for the 4-in. size on pre-war basis or 100 per cent. higher in 1921.

878. Bus-bar Compartment Dimensions

Max. e.m.f. kv.	Bus size inches	Dimensions, inches A	B	C
15	1–2 × ¼	13	12⅜	5½
15	2–2 × ¼	13	12⅜	4½
15	1–3 × ¼	13	12⅜	5½
15	2–3 × ¼	13	12⅜	4½
22	wire	15	16½	8½
33	wire	18	19¼	9½
45	wire	25	26	13
66	wire	36	37	18
100	wire	56	56	28

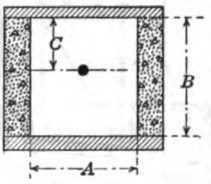


FIG. 131.

879. Spacing of High-tension Station Wiring

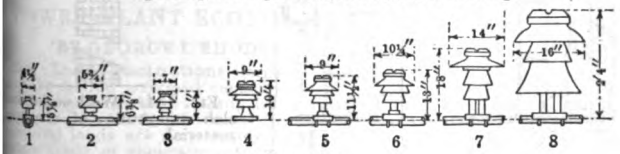


FIG. 132.

Number ref. to cut	E.m.f., volts	Spacing, inches	Ground distance, inches	Number ref. to cut	E.m.f., volts	Spacing, inches	Ground distance, inches
1	6,600	8	6	5	33,000	18	10 to 12
2	15,000	10	7	6	45,000	25	13
3	22,000	12	8 to 10	7	60,000	36	19
4	33,000	18	10	8	100,000	56	30

NOTE.—Ground distance (usually) = $\frac{\text{Wire spacing}}{2}$ + 1 in.

Spacing of series transformers (self-cooled):

600 volts.....	1 in. clear	6,600 volts.....	3 clear
2,300 volts.....	1.5 in. clear	13,200 volts.....	5 clear

880. Terminals and entrances, particularly on high-tension overhead outlets, require the most careful design to prevent leakage during bad weather. Standard designs are on the market supplied by the various insulator companies. Wall outlets are usually relatively simple and cheap, but satisfactory roof bushings are available only at considerable expense. The latter are similar to the oil switch and transformer terminals used for outdoor work. Several types are shown in Figs. 134–136.

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881. The cost of power-station wiring varies greatly and is exceed ingly difficult to estimate. The cost of wire, supports, insulators, etc can be obtained from manufacturers' lists, and usually an addition of fro 25 per cent. to 50 per cent. will cover the cost of labor, the larger percentag being for the smaller wires on pre-war basis or 50 to 100 per cent. for 192 The cost of drawing into conduits varied before the war from 1 cent to cents per duct ft. and from 3 to 10 cents in 1921. The cost of joints an terminals varies between that of 5 ft. and 10 ft. of wire. The total cost

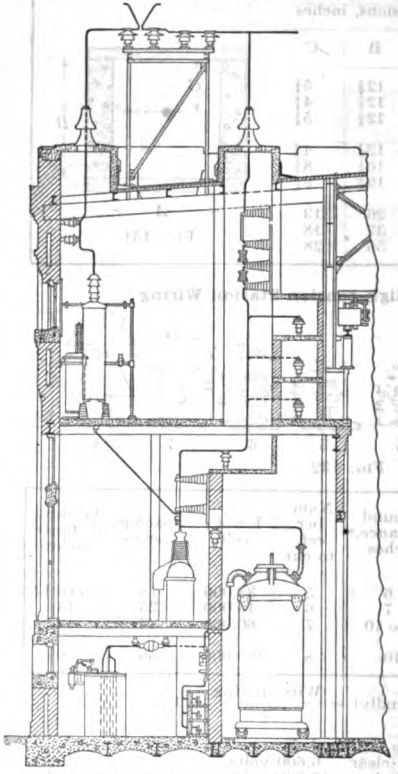


FIG. 133.—Cross section of transformer and switch galleries of high tension power station (*G.E. Rev.*, 1912, p. 598).

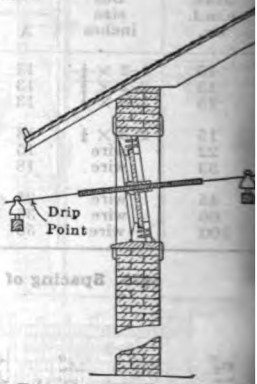


FIG. 134.—Wall outlet wi slab and tube of insulati material.

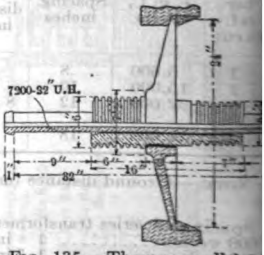


FIG. 135.—Thomas wall bus ing for 66,000 volts.

wiring varied before the war from $0.50 to $3 per kw. of station capacity 100 per cent. more on 1921 basis in addition to the cost of switch gear, pan and compartments.

MISCELLANEOUS

882. Plant location. Electrical considerations seldom have prepo derating influence on the location or general arrangement of a power statio

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The location affects the cost of the distribution system, for moderate and low voltages, directly as the square of the average distance of the load; on high-potential systems, the variation is more nearly proportional to the distance. Other conditions being equal, however, it is obvious that the best location is as near as possible to the **load centre.**

883. Parallel operation. Large systems frequently require the parallel operation of power stations, and little difficulty is ordinarily experienced. In some cases where plants in close proximity are thus operated, the service conditions require that the stations shall not be automatically disconnected from each other except in case of trouble in the tie lines. In other cases provision is made for the immediate disconnection of the stations in case of trouble in either. The latter arrangement is used where there is no connection between the systems supplied by the stations, other than directly between the station bus bars. Where stations are widely separated, parallel operation is not satisfactory when the resistance drop in the connecting lines exceeds 15 per cent. on alternating-current systems and 50 per cent. on direct-current systems. The operation of such **interconnected systems** requires careful arrangement, frequently making it necessary to have a **load dispatcher** in full control of all switching operations.

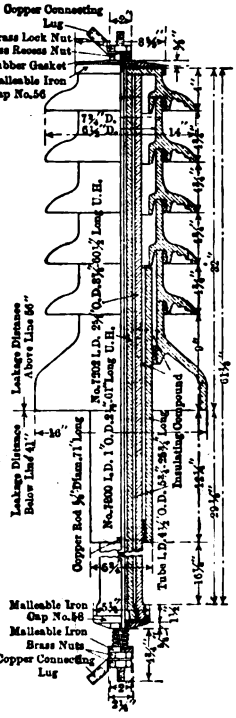


FIG. 136.—Thomas roof insulator for 66,000 volts.

POWER-PLANT ECONOMICS

BY GEORGE I. RHODES

884. Load fluctuations largely determine the desired overload capacity of units. Lighting systems have steady loads except for peaks shown by the usual load curve. Industrial loads are very steady except for certain kinds of applications to intermittent work using large units. Railway loads have considerable fluctuation even in the largest systems. Swings of five times the average are experienced when but a single car is running, twice, when about ten are running, and to 120 per cent. when a very large number are running.

885. Sudden peaks are always a possibility on a lighting system, and occur whenever a sudden storm appears. An increase of load of as much as 100 per cent. within a very few minutes is not uncommon.

886. The load factor of a machine, plant, or system is the ratio of the average power to the maximum power during a certain period of time. The average power is taken over a period such as a day, or a year, and the maximum is taken over a short interval of the maximum load within that period. In each case the interval of the maximum load should be definitely specified. The proper interval is usually dependent upon local conditions and upon the purpose for which the load factor is to be determined. The yearly average of daily load factors is frequently used. (See Sec. 25.)

887. Diversity factor is the ratio of the sum of the maximum power demands of the subdivisions of any system or part of a system, to the maximum demand of the whole system or of the part of the system under consideration, measured at the point of supply.

888. The load to be carried is probably the most important factor to be

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considered in power-plant design. It determines the size of plant, the kind of plant, and the size and number of units. **Typical load curves** are shown in Figs. 137 and 138. These curves are such as would be obtained from 15-min. readings of watt-hour meters but do not show the exact load on

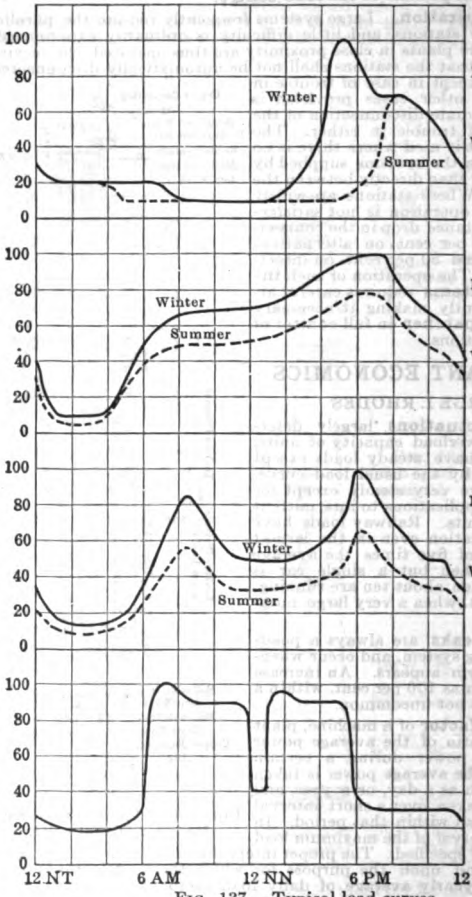


FIG. 137.—Typical load curves.

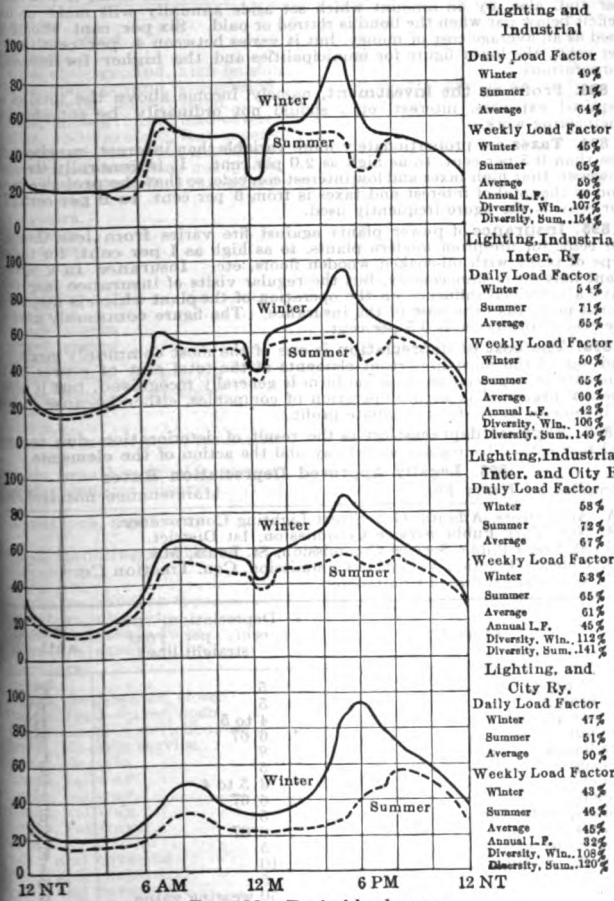
any specific plant. For typical load curves in very large central station see *Trans.* A. I. E. E., Vol. XXXI, p. 1473, 1912.

889. Demand factor is the ratio of the maximum power demand of an system or part of a system to the total connected load of the system, or the part of the system under consideration.

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890. Capacity factor is the ratio of the average load to the total rated capacity of the equipment supplying that load. This factor is not very definite on account of variations in methods of rating apparatus.

891. Fixed charges as ordinarily defined with reference to power plants, are the charges necessary to carry the investment and to replace the equip-



Lighting and Industrial

Daily Load Factor
Winter 49%
Summer 71%
Average 64%

Weekly Load Factor
Winter 45%
Summer 65%
Average 59%
Annual L.F. 40%
Diversity, Win. .107%
Diversity, Sum. .154%

Lighting, Industrial, Inter. Ry

Daily Load Factor
Winter 54%
Summer 71%
Average 65%

Weekly Load Factor
Winter 50%
Summer 65%
Average 60%
Annual L.F. 42%
Diversity, Win. .106%
Diversity, Sum. .140%

Lighting, Industrial, Inter. and City Ry.

Daily Load Factor
Winter 58%
Summer 72%
Average 67%

Weekly Load Factor
Winter 53%
Summer 65%
Average 61%
Annual L.F. 45%
Diversity, Win. .112%
Diversity, Sum. .141%

Lighting, and City Ry.

Daily Load Factor
Winter 47%
Summer 51%
Average 50%

Weekly Load Factor
Winter 43%
Summer 46%
Average 45%
Annual L.F. 32%
Diversity, Win. .108%
Diversity, Sum. .120%

FIG. 138.—Typical load curves.

ment when it is worn out or destroyed. Interest and taxes carry the investment, while insurance and accumulated depreciation funds cover replacement.

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892. Interest as used in engineering computations is the annual co of the money required for the work. It is affected by the credit of t company and the condition of general business at the time money is bo rowed. If money is raised by bonds sold below par, as is frequently t case, the cost of money is not only the only interest rate on the bond, b this amount is increased in proportion to the amount the bond is sold bel par and, also, by an amount which set aside annually will make up th deficit below par when the bond is retired or paid. Six per cent. should used as an average cost of money, but it varies between 4 per cent. and per cent., the lower figure for municipalities and the higher for industr corporations.

893. Profit on the investment, namely, income above the total of required expenses, interest, etc., should not ordinarily be considered engineering work.

894. Taxes are proportionately more variable than interest, ranging fro less than 0.5 per cent. to as high as 2.0 per cent. It is generally the ca however, that high taxes and low interest coincide, so that the probable vari tion of the total of interest and taxes is from 6 per cent. to 9 per cent.; 7 per cent. is the figure frequently used.

895. Insurance of power plants against fire varies from less than 0 per cent. for fire-proof modern plants, to as high as 1 per cent. for the o type of plant with oil-soaked wooden floors, etc. Insurance in a mode plant may seem unnecessary, but the regular visits of insurance inspecto have a beneficial influence on the operation of the plant which is frequent worth more than the cost of the insurance. The figure commonly used i the cost of insurance is 0.5 per cent.

896. The cost of depreciation is one of the most commonly neglect and one of the most important elements of the total cost of power. T existence of depreciation in some form is generally recognized, but it is fr quently neglected in actual operation of companies, either because of la of income or desire for immediate profit.

897. Physical depreciation is the result of deterioration due to we and tear caused by regular use, decay and the action of the elements.

898. Legally Approved Depreciation Rates

Compiled by Henry Floy. Maintenance not include

A. Arbitrators, Atlanta, Ga., Street Lighting Controversy.
B. New York Public Service Commission, 1st District.
C. St. Louis Public Service Commission, St. Louis, Mo.
D. Chicago Traction Valuation Commission, Con. Traction Co.
E. Wisconsin Railroad Commission.

Property	Depreciation, per cent. per year (straight line)	Key to authority
Aerial lines	5	C
Air brakes	5	E
Air compressors	4 to 5	D
Arc lamps	6.67	E
Arc lamps	8	C
Belting	5	E
Boilers	3.5 to 4	D
Boilers	6.67	C
Boilers, water-tube	5	B
Boilers, fire-tube	6.67	E
Boilers, water-tube	5	E
Boilers, fire-tube	10	A
Bonds	5	D
Bonds	50 wearing value	B
Bonds	5	E
Breeching and connections	3.5 to 10	D
Buildings	1.5	D
Buildings, brick	2	B

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898. Legally Approved Depreciation Rates.—(*Continued*)

Property	Depreciation per cent. per year (straight line)	Key to authority
Buildings	2 to 4	E
Buildings, wood	2	C
Buildings	2	A
Cables, underground, high-tension	5	B
Cables, underground, low-tension	50 maintenance cost	B
Cables, aerial, lead-covered	6.67	E
Cables, underground, lead-covered	4	E
Cables, underground, lead-covered	5	C
Coal and ash handling machinery	7	D
Coal and ash handling machinery	5	B
Coal and ash handling machinery	10	E
Condensers	4	D
Condensers	5	B
Condensers	5	E
Condensers	6.67	C
Conduits	1	B
Conduits	2	E
Conduits	2	C
Cross-arms	8.33 to 12.5	E
Engines, steam	3 to 5	D
Engines, steam	5 to 7.5	B
Engines, gas	6.67	E
Engines, steam, slow-speed	5	E
Engines, steam, high-speed	6.67	E
Engines	5	A
Engines	6.67	C
Feeders, weather-proof insulation	Dependent on observed wear	D
Feeders, weather-proof insulation	6.25	E
Foundations, machinery	Same as life of apparatus supported	D
Foundations, machinery	Same as life of apparatus supported	B
Fuel-oil handling machinery	4	D
Generators	3 to 8	D
Generators	5	B
Generators, modern type	5	E
Generators, obsolete	6.67	E
Generators, steam turbo	5	E
Generators, steam turbo	10	A
Generators	6.67	C
Heaters	4 to 6	D
Heaters, feed-water, closed	3.33	E
Heaters, feed-water, open	3.5	E
Meters, electric switchboard	5	E
Meters, electric service	6.67	E
Meters, electric	8	C
Motors, railway	3.33	D
Motors, railway	By inspection	B
Motors, railway	5	B
Motors, railway	5	E
Paving	50 wearing value	B
Piping and covering	4 to 4.5	D
Piping and covering	5 to 6	B
Piping and covering	5	E
Piping and covering	5	A
Piping and covering	6.67	C
Poles, steel	2	B
Poles, wood in concrete	5	E
Poles, wood in earth	5.5 to 8.33	E

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898. Legally Approved Depreciation Rates.—(*Continued*)

Property	Depreciation, per cent. per year (straight line)	Key to authority
Poles, iron	2.5	E
Poles, wood	10	A
Pumps	5	D
Pumps	5	B
Pumps, small steam	6.67	E
Pumps	5	A
Pumps	6.67	C
Rolling stock, open car bodies	4	D
Rolling stock, open trailer bodies	4	D
Rolling stock, closed car bodies	5	D
Rolling stock, trucks	3.33	D
Rolling stock, closed & open cars	3.33	B
Rolling stock, trucks	3.33	B
Rolling stock, car bodies and equip.	6.67	E
Stack	3	D
Stack, steel	10	B
Stokers, fixed parts	5	D
Stokers, moving parts	20	D
Storage batteries	5	B
Storage batteries	6.67	E
Storage batteries	5	C
Switchboard and wiring	3	D
Switchboard and wiring	6	B
Switchboard and wiring	5	E
Switchboard and wiring	8	C
Telephones	10	E
Track, rail joints	5	D
Track, ties	5	D
Track, rails	Dependent on observed wear	D
Track, special work	8.33	E
Track, straight and special work	50 % wearing value	B
Track, straight track	5.5	E
Transformers, station service	5	E
Transformers, station service	6.67	C
Turbines, steam	5	E
Turbines, water	3.33	E
Turbines, steam	6.67	C
Wire, trolley	Allowance of 80.5 lb. per 1,000 ft. for wear-wearing value of No. 0 wire	D
Wire, trolley	Allowance of 106.8 lb. for No. 00 wire.	D
Wire, trolley No. 0, under 1 min. headway	50	E
Wire, trolley No. 00, under 1 min. headway	40	E
Wire, trolley, No. 000, under 1 min. headway	33.3	E
Wire, weather proof	6.25	E
Wire, weather proof	7.5	A
Wire, weather proof	50 % maintenance cost	B

899. Functional depreciation is the result of lack of adaptation t function, caused by **obsolescence** and **inadequacy.** Obsolescence is du to changes or advances in the art which renders a piece of apparatus, or whole class of it, obsolete and uneconomical of use, as compared with ne types which have been developed at a later date and which are much mo efficient (H. G. Stott, *Trans.* A. I. E. E., p. 1619, 1913).

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900. Life expectancy of equipment. The life expectancy of power-plant equipment, taking functional depreciation into account, is as follows:*

Property	Total life (years)	Scrap value, per cent. of original cost
Buildings	75	5
Boilers, stokers and furnaces	20	5
Conveyers, elevators and hoists	20	1
Turbines, complete	12	10
Engines and condensers	12	10
Piping, values and traps	12	3
Pumps	12	5
Synchronous converters, transformers and exciters, etc.	20	10
Switching apparatus and instruments	12	5
Alternators	12	10
Motors	20	10
Tools and sundries	10	3
Storage batteries	10	10

901. Scrap value. It is obvious that in computing the net annual amount of depreciation the scrap value of the apparatus must be deducted from the original or first cost.

902. Methods of caring for depreciation. Charging to repairs all replacement of apparatus, either in part or as a whole, is expected in many companies to care for depreciation. Ordinary repairs will not prevent a machine from finally reaching a point, due to wear and tear, where it will have to be replaced and in small companies this replacement would cost such a large proportion of the total investment that it is desirable to accumulate a fund for the purpose. If replacements are charged to repairs this item will become irregular in amount, which is a very undesirable condition. In very large companies the irregularity becomes less and consequently the method can be used with success.

903. The straight-line method of computing depreciation is based on the assumption of a uniform reduction in value. It is commonly assumed that the accumulated depreciation fund, under this method, bears no interest, but such is not necessarily the case. The method has the great advantage of being very simple in application.

904. The amortization or sinking fund method of computing depreciation assumes that the accumulated depreciation fund is invested and bears interest. The effect is to make the annual rate less, of course, than it would be if the fund bore no interest. This method is not easy of application to actual conditions. Some authorities consider that it represents, more nearly than the straight-line method, the depreciation in actual value of the property as determined by what a purchaser could afford to pay for it.

905. Calculations of depreciation, by whatever method, should be made separately for each type of equipment, taking into account its expected life and its scrap value. There is much chance for error in deciding on a percentage to apply to an entire property, and if used it should be determined from a detailed calculation. It is evidently subject to some variation from time to time as new equipment is added.

906. Obsolescence is commonly regarded as a type of depreciation to be charged to the cost of power. This is not necessarily the case. Obsolescence does not accrue from day to day, like physical depreciation, but accrues coincidently with advances in the art resulting in new and more efficient machinery or methods. The full physical life of equipment is possible in any event, whether or not obsolescence occurs, and the question whether a piece of equipment should be replaced before it wears out is determinable by equating the saving in operating expenses against increased

* Stott, H. G., "Power Costs"; *Trans.* A. I. E. E., 1913, Vol. XXXII, p. 1112.

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fixed charges. In comparing different types of plants it is misleading to consider obsolescence as different for the various types.

Physical and functional depreciation costs must not be added. If functional depreciation will shorten the expected life the proper rate to care for this shortened life should be used, which includes physical depreciation. Eminent engineers have incorrectly allowed a percentage for physical depreciation and an additional percentage for functional depreciation.

907. Summary of H. G. Stott's Classification of Operating and Maintenance Costs

(Material and labor separated for each item)

Production costs	Production repairs costs
Management and care	Furnaces and boilers
Boiler room	Boiler accessories
Engine room	Engines
Electrical	Engine accessories
Fuel for steam	Piping
Water for steam	Electric generators
Lubricants	Electrical accessories
Supplies	Tools
Station expense	Building
General	General

908. Power cost data given in this section of the handbook represent as nearly as possible the **present state of the art** rather than old information. For instance, a great deal of data are available in reports to the various public service commissions which gives costs far in excess of these indicated here. In almost every instance the reporting companies operated plants which contain a great deal of inefficient apparatus maintained at great expense but for less cost than the fixed charges of new apparatus. Companies operating modern plants also frequently operate old plants, but do not report them separately. While these reports give valuable data as to what is being done under old designs, they are of little use for the purpose of estimating costs in truly modern plants.

909. Boiler Room Equipment Costs per Rated Boiler Horse-power using Coal for Fuel*

	Dollars per h.p.	
	High*	Low*
Boilers exclusive of masonry setting	$11.00	$8.00
Superheaters	3.00	0
Stokers	5.50	3.00
Masonry settings for boilers	3.50	2.00
Flues	1.50	0.75
Stacks	4.00	2.00
Economizers	4.00	0
Mechanical draft	3.00	0
Feed pumps	1.50	0.60
Feed heaters	1.00	0.40
All piping and pipe covering	10.00	6.00
Coal chutes and ash hoppers	1.25	0
Various, such as indicating and recording devices, damper regulator, ladders and runways, painting, etc., etc	1.00	0.50
Totals	$50.25	$23.15

* Lyford & Stovel, Proc. E. S. of W. P., Jan., 1912.
* For 1920–21 costs add 100 per cent. to high costs and 75 per cent. to lo

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910. Classification of operating expenses. A very complete form of cost analysis has been given by Mr. H. G. Stott, whose paper* should be consulted for details. His summary is presented in Par. **907**.

911. Analysis of the Average Losses in the Conversion of 1 Lb. of Coal into Electricity†

	B.t.u.	Percent.	B.t.u.	Percent.
1. B.t.u. per pound of coal supplied	14,150	100.		
2. Loss in ashes			340	2.4
3. Loss to stack			3,212	22.7
4. Loss in boiler radiation and leakage			1,131	8.0
5. Returned by feed-water heater	441	3.1		
6. Returned by economizer	960	6.8		
7. Loss in pipe radiation			28	0.2
8. Delivered to circulator			223	1.6
9. Delivered to feed-pump			203	1.4
10. Loss in leakage and high-pressure drips			152	1.1
11. Delivered to small auxiliaries			51	0.4
12. Heating			31	0.2
13. Loss in engine friction			111	0.8
14. Electrical losses			36	0.3
15. Engine radiation losses			28	0.2
16. Rejected to condenser			8,524	60.1
17. To house auxiliaries			29	0.2
	15,551	109.9	14,099	99.6
	14,099	99.6		
Delivered to bus bar	1,452	10.3		

912. Analysis of Thermal Losses in Power Plants ‡

Range of Common Practice

British thermal units per pound of fuel	14,000
Average yearly overall boiler and furnace efficiency	50 to 70
Effective British thermal units per pound of fuel	7,000 to 9,800
Boiler pressure, pounds per square inch, gage	125 to 190
Superheat, degrees Fahrenheit	0 to 125
Average feed-water temperature, degrees Fahrenheit	120 to 200
British thermal units per pound of steam (approx.)	1,100 to 1,100
Pounds of water evaporated per pound of fuel, actual	6.36 to 8.91
Pounds of fuel per standard boiler h.p. (33,305 b. t. u. s)	4.76 to 3.40
Average overall station water rate kw	30 to 20
Pounds of coal per k.w. generated	4.72 to 2.35
British thermal units in coal per kw. generated	66,000 to 31,500
Thermal efficiency of station	5.2 % to 10.8 %

* Stott, H. G. and Gorsuch, W. S., "Standardization of Method for Determining and Comparing Power Costs in Steam Plants;" *Trans.* A. I. E. E., 1913, p. 1099.

† H. G. Stott, "Power-plant Economics," *Trans.* A. I. E. E., 1906, p. 3.

‡ Lyford & Stovel, Proc. E. S. of W. P., Jan., 1912.

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913. Power Plant Costs per Kilowatt
(H. G. Stott)

	Min.	Max.
1. Real estate	$3.00	$7.00
2. Excavation	0.75	1.25
3. Foundations, reciprocating engines	2.00	3.00
4. Foundations, turbines	0.50	0.75
5. Iron and steel structure	8.00	10.00
6. Building (roof and main floor)	8.00	10.00
7. Galleries, floors, and platforms	1.50	2.50
8. Tunnels, intake and discharge	1.40	2.80
9. Ash storage pocket	0.70	1.50
10. Coal hoisting tower	1.20	2.00
11. Cranes	0.40	0.60
12. Coal and ash conveyors	2.00	2.75
13. Ash cars, locomotives, and tracks	0.15	0.30
14. Coal and ash chutes	0.40	1.00
15. Water meters, storage tanks, and mains	0.50	1.00
16. Stacks	1.25	2.00
17. Boilers	9.50	11.50
18. Boiler setting	1.25	1.75
19. Stokers	1.30	2.20
20. Economizers	1.30	2.25
21. Flues, dampers, and regulators	0.60	0.90
22. Forced draft blowers, air ducts	1.25	1.65
23. Boiler, feed, and other pumps	0.40	0.75
24. Feed-water heaters	0.20	0.35
25. Piping, traps, and separators	3.00	5.00
26. Pipe covering	0.60	1.00
27. Valves	0.60	1.00
28. Main engines, reciprocating	22.00	30.00
29. Exciter engines, reciprocating	0.40	0.70
30. Condensers, barometric or jet	1.00	2.50
31. Condensers, surface	6.00	7.50
32. Electric generators	16.00	22.00
33. Exciters	0.60	0.80
34. Steam-turbine units, complete*	$10.00	$15.00
35. Converters, transformers blowers	0.60	1.00
36. Switchboards, complete	3.00	3.90
37. Wiring for lights, motors, etc	0.20	0.30
38. Oiling system	0.15	0.35
39. Compressed air system and other small auxil	0.20	0.30
40. Painting, labor, etc	1.25	1.75
41. Extras	2.00	2.00
42. Engineering expenses and inspection	4.00	6.00

914. Analysis of the Average Losses in the Conversion of 1 Lb. of Co Containing 12,500 B.t.u. into Electricity. Producer Gas Engine Plant†

	B.t.u.	Per cent.
1. Loss in gas producer and auxiliaries	2,500	20.0
2. Loss in cooling water in jackets	2,375	19.0
3. Loss in exhaust gases	3,750	30.0
4. Loss in engine friction	813	6.5
5. Loss in electric generator	62	0.5
6. Total losses	9,500	76.0
7. Converted into electrical energy	3,000	24.0
	12,500	100.0

*Edited by Author. Add 100 per cent. to minimum and 80 per cent. maximum costs for 1920–21.

† H. G. Stott, "Power Plant Economics," *Trans.* A. I. E. E., 1906, p. 3

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915. Cost of 1 H. P. per Year, Compound Condensing Engines, 10-hr. basis, 306 Days per Year*
(Wm. O. Webber, Engineer U. S., Feb. 2, 1903, p. 144)

Size of plant	Horse-power			
	200	600	1,000	2,000
Cost of plant per horse-power	$146.00	$85.00	$60.00	$56.00
Fixed charges at 14 per cent.	24.40	11.90	8.40	7.85
Coal per horse-power hour, pounds	6.5	4.5	2.5	1.5
Cost of fuel at $4.00 per ton	35.70	24.70	13.75	8.25
Attendance, 10-hr. basis	10.00	5.40	3.50	3.00
Oil, waste, supplies	2.00	1.08	0.70	0.60
Total	68.10	43.08	26.35	19.70
With coal at $5.00 per ton.	77.10	49.28	29.80	21.75
With coal at $4.00 per ton.	68.10	43.08	26.35	19.70
With coal at $3.00 per ton.	59.20	36.88	22.90	17.65
With coal at $2.00 per ton.	50.25	30.73	19.47	15.57

916. Example of operating expense. Operating and maintenance costs for four twelve month periods to June 30, 1919, indicating the relatively increasing expenses experienced by the Detroit Edeson Connor's Creek station are summarized as follows:

†Cost per kw.-hr. output for 12 months period ending June 30.

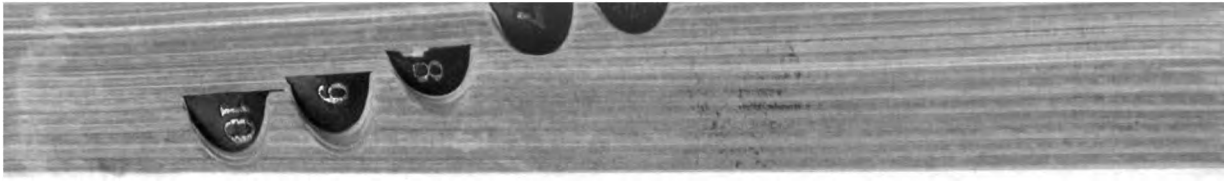
Items	1916	1917	1918	1919
Oper.—Wages and supt.	$0.0056	$0.0057	$0.0064	0.0072
Fuel	0.0158	0.0240	0.0368	0.0394
Lubricants	0.0001	0.0001	0.0001	0.0002
Supplies and exp.	0.0005	0.0005	0.0006	0.0010
Maint.—Buildings	0.0006	0.0011	0.0008	0.0010
Steam equip.	0.0019	0.0019	0.0025	0.0024
Elec. equip.	0.0003	0.0001	0.0002	0.0001
Total—Oper. and maint.	$0.0248	$0.0334	$0.0474	$0.0513
Thous. kw.-hr. out	125,159	210,040	280,815	383,252
Max. 30 min. demand	35,000	50,000	59,000	82,000
Aver. kw. load	14,000	23,900	32,100	43,700
Load factor	0.409	0.478	0.544	0.533
Lb. coal per kw.-hr.	1.44	1.52	1.63	1.67
B.t.u. per kw.-hr.	19,700	20,040	20,940	21,200
B.t.u. per lb. coal	13,670	13,180	12,840	12,630
Aver. coal cost, ton	$2.19	$3.16	$4.52	$4.72

917. National Electric Light Association, Form for Power Cost Record. (*Condensed*)

1. Station Wages:
(a) Superintendence and office force. (b) Boiler labor. (c) Engine labor. (d) Electrical labor. (e) Miscellaneous labor.
2. Fuel.
3. Water:
(a) Feed water. (b) Condensing water. (c) House water.
4. Lubricants.
5. Station supplies and expense:
(a) Supplies. (b) Expense.
6. Station Buildings: maintenance, including labor: (a) Structure. (b) Fittings.
7. Steam Equipment: maintenance, including labor: (a) Boilers and furnaces. (b) Boiler auxiliaries. (c) Piping. (d) Prime movers. (e) Mechanical apparatus. (f) Tools and instruments.
8. Electrical Equipment: maintenance, including labor:
9. Hydraulic Equipment: maintenance, including labor. (a) Dam and pipe lines, etc. (b) Turbine and gates.
10. Gas Equipment: maintenance, including labor: (a) Gas engines and auxiliaries. (b) Other apparatus.
11. Purchased Power.

* Gebhardt, "Steam Power Plant Engineering," p. 711. A.S.M.E. *x*–48. Add 100 per cent. to Plant Costs for 1921.
† *Electrical World*, Vol. 74, p. 656.

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918. Unit Costs of Hydroelectric Developments
(O. S. Lyford, Trans. A. I. E. E., 1909)

Plant	A	B	C	D	E	F	G
Land and water rights	Cash $14.10	cost $12.86	per $8.89	kilowatt $14.20	of $22.22	generator $13.07	capacity $15.00
Hydraulic construction (dam, canals, flumes, head-gates, *etc.* Power house building and substructure	35.00	43.41	49.50	44.53	51.30	62.42	56.71
Hydraulic equipment	14.00	13.95	13.00	9.05	7.76	7.84	7.56
Power house electrical equipment	21.00	22.73	19.20	13.85	14.50	13.53	12.50
Transmission line, including right of way	17.20	6.26	18.30	9.00	20.70	17.50	28.50
Substation buildings and equipment	5.72	6.51	9.75	7.55	6.82	8.40	8.40
Distribution system	10.00	6.94	4.58	4.45	15.67	14.58	12.00
Interest during construction	6.30	7.36	5.54	4.75	8.40	6.18	6.16
Engineering	5.90		6.14	6.30	7.00	6.87	6.84
General and legal exp	3.70		6.20	4.45	5.77	7.48	6.84
Total	$132.92	$120.02	$141.10	$118.13	$160.14	$157.87	$160.51

Note.—For 1919–20 costs add 100 per cent. to Construction Items. See *Elec. World*, Mar. 1, 1919; April. 24, 1920; Mar. 27, 1920. *Power*, Apr. 8, 1919.

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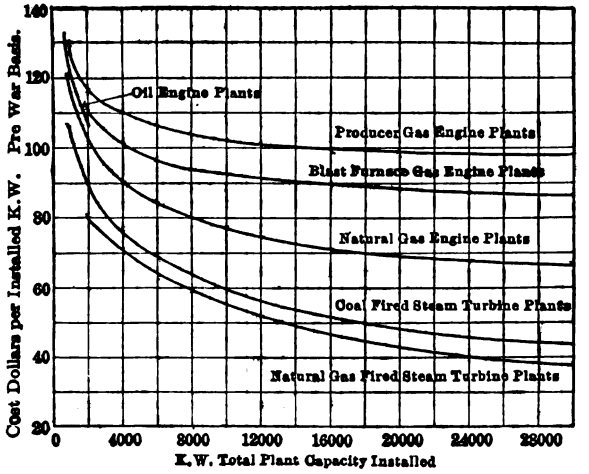


FIG. 139.—Plant installment costs (E. D. Dreyfus, *Elec. Jour.*, 1912)

919. Cost of Producer Gas Installations, 1912
(Bureau of Mines Bulletin No. 55, p. 29)

Horse-power	Cost of gas producer and engine erected, including foundations	Cost of complete plant, exclusive of buildings (a)	Cost of complete plant, including buildings (a)	Cost per horse-power: Gas producer and engine erected, including foundations	Cost per horse-power: Complete plant, exclusive of buildings (a)	Cost per horse-power: Complete plant, including buildings (a)
50	$4,300	$5,300	.....	$86.00	$106.00	.....
100	6,250	7,800	$9,100	62.50	78.00	$91.00
200	12,400	15,800	17,500	62.00	79.00	87.50
200	13,200	16,200	.....	66.00	81.00	.....
250	14,800	18,200	.....	58.20	72.80	.....
300	17,000	22,000	23,800	56.65	73.35	79.35
500	25,000	29,500	.....	50.00	59.00	.....
500	32,500	47,500	.....	65.00	95.00	.....
1,000	48,500	57,500	.....	48.50	57.50	.....
1,000	56,000	84,000	.....	56.00	84.00	.....
3,000	145,500	202,000	.....	48.50	67.35	.....

(a) Includes producer, engine, electric generator, piping, switchboard and auxiliaries, all erected with suitable foundations.

920. Influence of load factor on cost of power.
(a) **Fixed charges.** It is obvious that this cost varies inversely as the load factor. It is important, however, that the proper factor be used, namely the annual capacity factor of the total equipment installed.
(b) **Operating labor.** It is obvious that in small plants, or plants of very few units, a large amount of labor is unaffected by the load on the
Note.—Add 85 per cent. for 1920–21 costs.

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plant. As the number of units increases, this portion becomes relatively smaller. It is probable that the ratio of full-load labor costs per hour to no-load costs varies from 2 to 1 in plants of a single unit, to 5 to 1 in plants of a large number of units.

(c) **The coal** required to maintain a plant ready for instant service with one unit running at no-load, consists of that required for its no-load steam, that of the auxiliaries and that for banked fires under sufficient boiler capacity to carry the peak load. This total no-load coal ranges from 25 per cent. of full-load coal in a plant of one unit to 8 per cent. in a plant of many units.

(d) **Operating repairs** and other expenses are very indefinite and uncertain except over a long period of time, but probably vary in direct proportion to the load, thus being independent of the load factor.

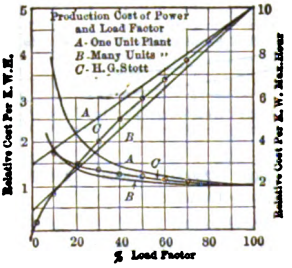


FIG. 140.—Variation in cost of power with load factor.

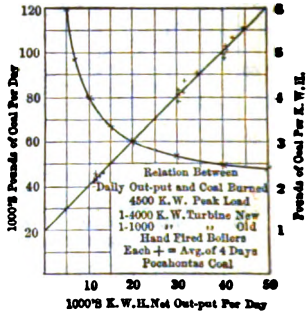


FIG. 141.—Variation in coal consumption with load factor.

(e) **Total production cost** at no-load varies from 30 per cent. of that at full load in plants of a single unit, to 10 per cent. in plants having many units. Mr. H. G. Stott has found that experience shows a variation in cost per kw.-hr. inversely as the fourth root of the load factors. Curves showing these cost are given in Figs. 140 and 141.

(f) **Period of load factor.** Since the no-load costs in a station are determined largely by the peak load expected during the month or week, it is evident that load factors for a shorter period than a year are advisable. Possibly the average daily or weekly load factor will give the best method of comparing these costs.

921. Comparison of power costs in different plants will lead to unreliable results unless certain fundamental conditions are taken into account. The chief of these are:

(a) **Certainty that costs include the same items** for each plant. Management, general expenses and building repairs are frequently omitted and care must be exercised to ascertain just what makes up the total cost. Hence the necessity of standard methods of cost accounting.

(b) **Load factors** if different require reductions of costs to the same basis. Fixed charges are inversely as the first power, and operating costs inversely as the fourth root of the load factors. Variations from 20 per cent. to 60 per cent. can be compared closely by this method.

(c) **Coal costs must** be compared on some common basis such as the cost per 1,000,000 B.t.u. available after deducting the B.t.u. in the ash.

(d) **Labor costs** must be treated similarly on the basis of the average wage per hour per man.

(e) **Fixed charges** must be on the same basis, not necessarily with the same life of equipment, but with the same method of figuring depreciation costs. It is also important to know how much spare apparatus is being maintained and whether or not the plant is complete, or one in which there is room for considerable additional apparatus.

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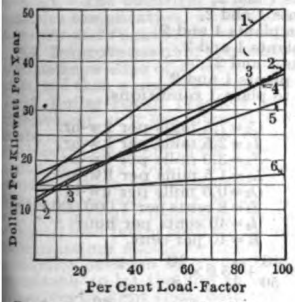


FIG. 142.—Coal cost $1.50 per ton; 11,000 B.t.u. per lb.*

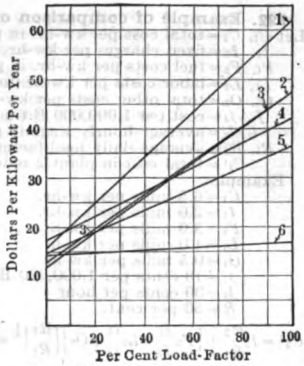


FIG. 143.—Coal cost $3.00 per ton; 14,500 B.t.u. per lb.*

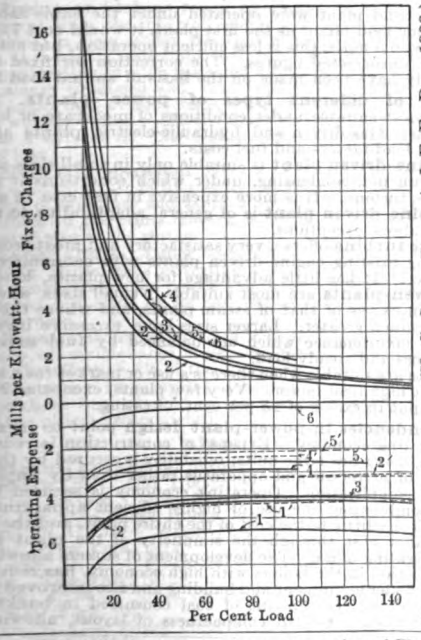


FIG. 144.—Cost of energy. (H. G. Stott, *Trans.* A. I. E. E., Dec., 1908.)
Line 1, Reciprocating steam plant; line 2, steam turbine plant; line 3, engines and low pressure turbines; line 4, gas engine plant; line 5, gas engine and steam turbine plant; line 6, hydraulic plant.
Coal cost $1.50 per ton; 11,000 B.t.u. per lb., Fig. 142 and dotted lines, Fig. 144. Coal cost $3.00 per ton; 14,500 B.t.u. per lb., Fig. 143 and solid lines, Fig. 144.

*For significance of curve numbers, see caption of Fig. 144.

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922. Example of comparison of power costs.* Let C_1, C_2 = total cost per kw-hr. in plants 1 and 2,
I_1, I_2 = fixed charges per kw-hr. in plants 1 and 2,
F_1, F_2 = fuel costs per kw-hr. in plants 1 and 2,
L_1, L_2 = labor costs per kw-hr. in plants 1 and 2,
O_1, O_2 = total other costs per kw-hr. in plants 1 and 2,
f_1, f_2 = cost per 1,000,000 B.t.u. in plants 1 and 2,
l_1, l_2 = average hourly wage in plants 1 and 2,
R_1, R_2 = average daily load factors in plants 1 and 2
C_2' = total cost in plant 2 reduced to plant 1 conditions.

Example:

$C_1 = 6.5$ mills per kw-hr.	$C_2 = 7.5$ mills per kw-hr.
$I_1 = 2.0$ mills per kw-hr.	$I_2 = 2.5$ mills per kw-hr.
$F_1 = 3.0$ mills per kw-hr.	$F_2 = 3.0$ mills per kw-hr.
$L_1 = 1.0$ mills per kw-hr.	$L_2 = 1.5$ mills per kw-hr.
$O_1 = 0.5$ mills per kw-hr.	$O_2 = 0.5$ mills per kw-hr.
$f_1 = 10$ cents per 1,000,000 B.t.u.	$f_2 = 8$ cents per 1,000,000 B.t.u.
$l_1 = 30$ cents per hour	$l_2 = 40$ cents per hour
$R = 50$ per cent.	$R = 40$ per cent.

$$C_2' = I_2\frac{R_2}{R_1} + \left[F_2\frac{f_1}{f_2} + L_2\frac{l_1}{l_2} + O_2\right]\left[\frac{R_2}{R_1}\right]^{\frac{1}{2}} = 2.5\times\frac{40}{50} + \left[3.0\times\frac{10}{8} + 1.5\times\frac{30}{40} + 0.5\right]\left[\frac{40}{50}\right]$$

$$= 2.0 + [3.75 + 1\ 125 + 0.5]\,[0.945] = 7.08 \text{ mills per kw-hr.}$$

That is, if the second plant were operated under the same labor and fuel cost and the same load factor as the first plant, it would cost 7.08 mills per kw-hr., as against 6.5 mills; this is less efficient operation, but not as bad as indicated by the uncorrected figures. The correction for fixed charges should more properly have been made on the basis of annual load factors.

923. Suitability of different types of power plants. Steam electric plants are most suitable under conditions of moderate or low load factor and fuel costs. Gas-driven and hydraulic-electric plants are suitable only with high load factors and fuel costs.

The steam-engine-driven plant is suitable only in small sizes or where it is necessary to run non-condensing, under which conditions it is more economical than the turbine. It is more expensive in first cost in all sizes.

The **steam-turbine-driven plant** is of general adaptability to all sizes and loads with the above exceptions.

The **low-pressure turbine** offers a very satisfactory and most economical method of extending existing engine-driven plants with economy equal to best modern practice. It has little advantage for new plants, however.

Gas-engine driven-plants are most suitable in small sizes where first cost is not greatly in excess of that of steam plants, and where the difference in economy is much greater. Larger sizes have excessive investment costs and expensive maintenance which are balanced by fuel saving only with high load factors and steady load.

Hydraulic plants are suitable when there is a use or market for a seasons delivery of power at high load factor. Very few plants, except at Niagara have a summer output in excess of 25 per cent. of rating.

924. Modern tendencies in power-plant design point to inexpensive plants of high operating economy. Expense of construction is reduced by simplicity in design, using few large units; reliability is secured by the use of the highest quality of materials and apparatus rather than by duplication with its attendant complication. Operating economy is secured through better control of combustion, the use of highly efficient apparatus whose efficiency adds relatively little to the cost of the entire plant, and the attendant reduction in labor cost through the simplicity of the plant and the small number of operating units. The development of stokers allowing very high rates of evaporation in the boilers with high economy, has reduced the investment costs in boiler equipment and building and also improved operating economy by reducing the amount of coal consumed in banked fires. There is a strong tendency toward compactness of layout, allowing one

* Adapted from Stott, H. G., Gorsuch, W. S., *Trans.* A. I. I. E.

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sufficient floor space for the dismantling of apparatus during repair. The perfection of the mechanical design of turbo-generators permits the use of skeleton foundations in which the condenser can be placed with great space economy. The electrical switching equipment still has a tendency toward expensive complication, which the writer believes will gradually give way to simplicity and ruggedness, except in the largest plants.

925. Improvement of economy of existing plants requires, first of all, an accurate knowledge of all the elements entering into the cost in that particular plant, and then a gradual elimination of the elements producing inefficiency.

926. Boiler-room practice affords probably the most fruitful field for improvement, as it has hitherto been the most neglected. Numerous instruments, meters and devices are on the market which make possible a continual check on the efficiency of the boiler room. It is not only possible to know the overall efficiency, but to determine readily just what are the causes of inefficiency; there are automatic devices, also, which remove some of these causes. A careful study should be made as to the variation in efficiency with peak load and load factor, so that the inherent improvement in economy with good load factor shall not be mistaken for the results of better operation. Determinations should be made as to the proper number of boilers to use, the relation between active fire hours and banked fire hours, and just when it is profitable to let the fires go out. It is highly important that the boilers themselves be kept clean both inside and out; means are available to facilitate this work, both chemical and mechanical. The firemen should be carefully instructed in proper methods of firing and closely watched to see that they follow instructions.

927. Engine or turbine room operation offers a less fruitful field for improvement since the inherent economy of the units, more particularly of the turbines, is less under the control of the operators. With engines, however, it is highly important that valve settings be maintained properly. The proper loading of units has some influence on economy. The balance of exhaust steam produced and that needed for feed-water heating is particularly important at light loads, when ordinarily there is an excess of steam which is wholly wasted. Electric drive of some of the auxiliaries frequently serves as a corrective. Air leakage into the condenser is an important source of loss.

928. Electrical operation offers a relatively limited field for improvement in economy. It is frequently possible, however, by rearranging the ventilation of windings and keeping them properly clean, to carry a better average load on the prime movers, which adds to the economy and also to the effective size of the station.

929. Labor shifts. Labor costs can frequently be reduced by arranging overlapping shifts, thus providing the necessary men during peak loads, without unnecessary men before and after. The efficiency of labor should be measured not alone by its cost per kw-hr., but by the cost per unit of work performed.

930. Repairs should be made as soon as their necessity is discovered. A high grade of maintenance is usually cheaper than lax maintenance, and increases the effective life of the apparatus.

931. Economy in supplies does not mean cheap materials, but the choice of those best adapted to the work and which give the lowest total cost for the object accomplished.

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SECTION 11

POWER TRANSMISSION

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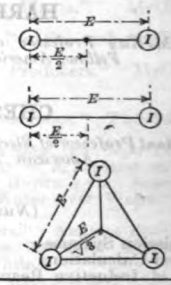
SECTION 11

POWER TRANSMISSION

TRANSMISSION SYSTEMS

1. Systems in common use. There are three systems in common use to-day: the direct-current (Thury) system, abroad only; the single-phase system, in railway work; and the three-phase system, for general transmission. These systems may be compared as follows, in terms of effective current and voltage.

Direct-current:	
Current per wire	$= I$
Voltage between wires	$= E$
Voltage to neutral	$= E/2$
Power	$= EI$
Single-phase:	
Current per wire	$= I$
Voltage between wires	$= E$
Voltage to neutral	$= E/2$
Power	$= EI \cos \theta$
Three-phase:	
Current per wire	$= I$
Voltage between wires	$= E$
Voltage to neutral	$= E/\sqrt{3}$
Power	$= \sqrt{3}EI \cos \theta$



2. Copper efficiency of the various systems*

	Relative current per wire	Relative voltage between wires	Relative loss per wire	Total relative conductor weight
Direct-current: Same max. voltage.	70.7	141	50	50
Same effective voltage	100	100	100	100
Single-phase	100	100	100	100
Three-phase	57.7	100	66.7	75

3. Direct-current (Thury) system.† Direct-current transmission is at present limited by the difficulty of obtaining a voltage sufficiently high for economical transmission, but Thury has developed in Europe a high-voltage, direct-current system, and a number of such plants are at present

* Voltage between wires, transmission distance, power transmitted and power loss are fixed; unity power-factor assumed. With the same effective voltage to *neutral*, all systems have the same copper efficiency.

† Still, Alfred. "The Thury System of Power Transmission by Continuous Currents." *Elec. World*, Vol. LX (1912), pp. 1093, 1144.

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giving satisfactory service (Fig. 1). The required line voltage is obtained by connecting series-wound generators in series, the voltage per commutator ranging from 1,300 to 4,000 volts. Each generator is mounted on an insulated platform and connected to its prime mover by an insulated coupling. When not in use, the generator is short-circuited. In this system the current is maintained constant by automatic devices which control the prime-mover speed, shift the brushes, and shunt the field, and the voltage is made to vary with the load. The power is delivered to motors similar in construction to the generators. The motor speed is controlled by shifting the brushes, and simultaneously shunting the field. Line voltages approximating 70,000 volts are in use, and a transmission distance of 112 miles (Moutier-Lyons) has been reached.

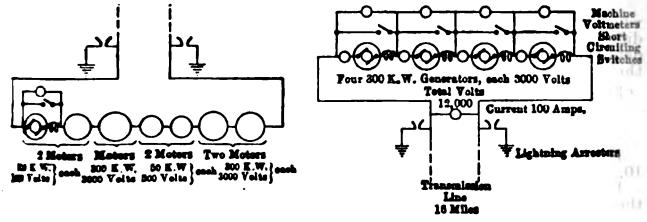


FIG. 1.—Typical Thury system.

4. Advantages claimed for Thury system: (a) power-factor always unity; (b) higher effective pressures for the same line insulation (tests by Thury indicate that with given line insulation, direct current may be twice the alternating current voltage). The maximum pressure occurs only during maximum loads; (c) no dielectric losses; (d) two wires only to be insulated; (e) underground single-conductor cable can be obtained for 60,000 volts, and with grounded neutral, the line pressure would be 120,000 volts; (f) no inductive or capacitive troubles such as surges and abnormal voltage rises; (g) a number of stations can be operated in series and a station can be connected to the line at any point; (h) switching arrangements very simple; (i) in hydraulic stations under variable head, greater efficiency can be obtained since constant speed is unnecessary; (j) adapted for industrial work requiring constant torque; (k) line repairs can be easily and safely made while the line is in operation after grounding the conductor at the point in question (not applicable to systems with grounded neutral).

5. Disadvantages of Thury system: (a) insulated floors and couplings; (b) generating units must necessarily be of moderate capacity, though several generators may be connected to one prime mover; (c) the line loss is constant and independent of the load, although the current may be somewhat decreased on light loads; (d) constant-head water-wheel not ideal for constant current (variable speed); (e) special regulating devices required on motors; (f) impossibility of securing overload torque on the motors, even for a short period; (g) greater liability of damage to generators, due to lightning, and hence more expensive protective devices are required.

6. Single-phase systems, except in occasional railway installations, are little used in transmitting large amounts of energy for great distances, since for a given voltage between lines, the copper efficiency is 75 per cent. of that of the three-phase system. For power purposes the single-phase motor is less satisfactory than the polyphase motor. The rating of a given generator when operating single-phase is about half its rating when operating polyphase.

7. Three-phase systems. Three-phase transmission and distribution are superseding the other systems, due to greater copper efficiency, the balanced condition of voltage (even under unbalanced loads) and the smaller number of conductors required in comparison with the two-phase system. The great flexibility of the three-phase system, and its advantages with respect to the use of both induction and synchronous machinery, are also important considerations in its favor.

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ELECTRICAL CALCULATIONS

8. The required size of conductor for a direct-current line may be readily estimated. With a given power, P watts, to be delivered at voltage, E_r, the value of current, I, is determined from the relation:

$$I = P/E_r \qquad \text{(amp.)} \qquad (1)$$

One mil-foot of copper has a resistance of about 10 ohms at 15 deg. cent. (62 deg. fahr.). If the conductor is operated at a normal current density of 0.001 amp. per cir. mil, the drop per ft. will be 0.01 volt, regardless of the size of conductor.

9. The total voltage drop may be expressed:

$$e = 0.01 \times l \qquad \text{(volts)} \qquad (2)$$

where l is the total length of conductor in ft. If the current density is different from this normal value, e will be in direct proportion to the current density. Thus, if the density is 1 amp. per 1,200 cir. mils, and $l = 100{,}000$ ft., then $e = 0.01 \times 100{,}000\ (1{,}000/1{,}200) = 833$ volts.

10. Efficiency of transmission may be expressed:

$$\eta = \frac{E_r}{E_r + e}\,100 \qquad \text{(per cent.)} \qquad (3)$$

If the receiver voltage in the above case were 10,500, then $\eta = 10{,}500/(10{,}500 + 833)$ or 92.6 per cent.

Power lost per mil-foot of copper at the normal density is represented by the expression:

$$I^2r = (10^{-3})^2\ 10 = 10^{-5} \qquad \text{(watts)} \qquad (4)$$

Total power lost at the normal density is

$$I^2R = 10^{-6} \times c.m. \times l \qquad \text{(watts)} \qquad (5)$$

where $c.m.$ is the conductor cross-section in cir. mils, and l is the total length of conductor in ft. If the current density differs from the normal, the right-hand side of Eq. 5 must be multiplied by the square of the ratio of the densities. Constant current high-voltage systems are usually so designed that the line losses are kept within prescribed limits.

If P, the power delivered, E_g, the generator voltage, and R, the line resistance be given, E_r, the receiver voltage, may be found from the following equation.

$$E_r = \frac{E_g}{2}\left[1 \pm \sqrt{1 - \frac{4PR}{E_g^2}}\right] \qquad \text{(volts)} \qquad (6)$$

The minus sign is only used when the efficiency of transmission is less than 50 per cent. which practically never occurs.

11. Example of design. Required to transmit 2,000 kw. 15 miles, with 10 per cent. line loss.

It is customary to allow 1,000 volts per transmission mile, but this may be modified somewhat by considerations of line cost. Assuming a pressure at the receiver of 15,000 volts, $I = 2{,}000{,}000/15{,}000 = 133$ amp. The permissible voltage drop = 1,500. Let e' = voltage drop at normal current density; then $e' = 0.01 \times 30 \times 5{,}280 = 1{,}584$ volts at normal density. Actual density must be $\dfrac{1{,}500}{1{,}584}$ amperes per 1,000 cir. mils. Hence the cir. mils required are

$$133 \times \frac{1{,}584}{1{,}500} \times 1{,}000 = 140{,}000.$$

12. The regulation and efficiency of a single-phase or a symmetrical polyphase system may be calculated by considering one conductor only, assuming a neutral which has zero resistance and zero reactance, as the return wire. A three-phase system may also be treated as a single-phase system transmitting one-half the power.

Sine waves of current and voltage, and balanced loads are assumed in the following paragraphs. The effects of harmonics and unbalancing can usually be neglected but may be treated as special problems if conditions warrant.

13. Alternating-current transmission-line calculations. A single-phase or symmetrical polyphase system having resistance per wire R ohms and reactance per wire X ohms and a load current to neutral of I amp. at power-factor, $\cos\theta$, is represented in Fig. 2 and the voltage relations are

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shown vectorially in Fig. 3. The electrostatic capacitance assumed to be negligible.

Knowing the receiver voltage, E_r, the generator voltage, E_g, may be readily calculated.

$$E_g = \sqrt{(E_r \cos\theta + IR)^2 + (E_r \sin\theta \pm IX)^2} \quad (7)$$

The minus sign is used when I leads E_r.
This may also be written

$$E_g = E_r \sqrt{\left(\cos\theta + \frac{IR}{E_r}\right)^2 + \left(\sin\theta \pm \frac{IX}{E_r}\right)^2} \quad (8)$$

Equation (8) is more convenient than (7) as the quantity under the radical sign is of the magnitude of unity and the position of the decimal point is more readily determined.

$$\text{Per cent. regulation} = \frac{E_g - E_r}{E_r} 100 \quad (9)$$

$$\text{Efficiency} = \frac{E_r I \cos\theta}{E_r I \cos\theta + I^2 R} \quad (10)$$

If the sending-end voltage, E_g, the load power P, in watts, and the load power-factor, $\cos\theta$, are fixed, E_r is found by the following equation:*

$$E_r = A \sqrt{1 \pm \sqrt{1 - \frac{(R^2 + X^2)P^2}{A^4 \cos^2\theta}}} \quad \text{where } A = E_g \sqrt{\tfrac{1}{2} - \frac{P(R\cos\theta + X\sin\theta)}{E_g^2 \cos\theta}} \quad (11)$$

For practical work it is usually more convenient to assume a regulation, find E_r from (9), and solve for E_g by the use of (8). If the calculated regulation then differs materially from that assumed, another trial may be necessary. If the receiver rather than the generator voltage be fixed, the problem is much simplified.

14. Example of single-phase calculation. Transmission distance, 20 miles; generating voltage, 33,000 volts; frequency, 60 cycles per sec.; full-load power-factor, 0.85; spacing of wires, 48 in.; permissible line loss, 10 per cent. of power generated.

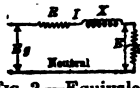


FIG. 2.—Equivalent transmission line to neutral.

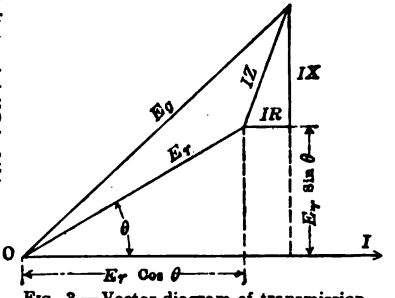


FIG. 3.—Vector diagram of transmission line.

Assumed power at receiver = 5,000 kw. Assuming 15 per cent. regulation, the e.m.f. at the receiver equals 28,700 volts, and the voltage from wire to neutral at the receiver is 14,350 volts. Current per wire = 5,000,000/(28,700 × 0.85) = 205 amp. Loss per wire = (0.10/0.90) × (5,000/2) = 278 kw. Resistance per wire = 278,000/(205)² = 6.61 ohms. Resistance per mile = 6.61/20 = 0.331 ohm.

From the table of Par. 40 the nearest size of wire is No. 000 A.W.G. copper, having 0.342 ohm per mile or a total resistance (20 miles) of 6.84 ohms.

Reactance per mile (Par. 40) of single conductor, 0.692 ohm. Total reactance, 13.84 ohms. IR = 1,400 volts, IX = 2,840 volts. Substituting in (8)

$$E_g = 14{,}350 \sqrt{\left(0.850 + \frac{1{,}400}{14{,}350}\right)^2 + \left(0.527 + \frac{2{,}840}{14{,}350}\right)^2} = 17{,}140 \text{ volts.}$$

$$\text{Regulation} = \frac{17{,}140 - 14{,}350}{14{,}350} 100 = 19.44 \text{ per cent.}$$

*See "*Electric Journal*," Vol. XVII, Feb. 1920, Page 76.

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The calculation shows material error. Assume 19 per cent. regulation,

$$I = 212 \text{ amps.}, \qquad IR = 1{,}450 \text{ volts}, \qquad IX = 2{,}940 \text{ volts}.$$

$$E_g = 13{,}870\sqrt{\left(0.850+\frac{1{,}450}{13{,}870}\right)^2+\left(0.527+\frac{2{,}940}{13{,}870}\right)^2} = 16{,}750 \text{ volts}.$$

The calculated regulation is then $\frac{16{,}750-13{,}870}{13{,}870}100 = 20.7$ per cent. As this checks closely with the 19 per cent. regulation assumed, another trial is unnecessary, unless greater refinement is desired.

The efficiency then becomes $n = 2{,}500{,}000/[2{,}500{,}000+(212)^2 6.84]$ or 89.1. With aluminum as the conductor, the reactance drop would be slightly less.

15. Example of three-phase calculation for a line having the same constants as are given in **Par. 14.** Transmission distance, 20 miles; generating station line voltage, 33,000 volts; frequency, 60 cycles; load power-factor, 0.85; spacing of wires, 48 in.; permissible line loss, 10 per cent. of power generated; power at receiver, 5,000 kw.; voltage to neutral, generating station, $33{,}000/\sqrt{3} = 19{,}050$ volts. Assuming 15 per cent. regulation, voltage at receiving station $= 19{,}050/1.15 = 16{,}570$ volts. Current per wire $= 5{,}000{,}000/(3\times 16{,}570\times 0.850) = 118.4$ amp. Loss per wire $= \frac{5{,}000}{3}\times\frac{0.10}{0.90} =$ 185 kw. Resistance per wire $= 185{,}000/(118.4)^2 = 13.20$ ohms. Resistance per mile $= 13.20/20 = 0.660$ ohm.

From **Par. 40** the nearest wire size is No. 1 A.W.G. which has a resistance of 0.683 ohm per mile.

Total resistance = $20\times 0.683 = 13.66$ ohms.
Reactance per mile (Table **42**) ..... 0.734 ohm.
Total reactance ..... 14.68 ohms.
$IR = 118.4\times 13.66 = 1{,}617$ volts $\qquad IX = 118.4\times 14.68 = 1{,}738$ volts

Substituting in (8)

$$E_g = 16{,}570\sqrt{\left(0.850+\frac{1{,}617}{16{,}570}\right)^2+\left(0.527+\frac{1{,}738}{16{,}570}\right)^2} = 18{,}870 \text{ volts}.$$

$$\text{Regulation} = \frac{18{,}870-16{,}570}{16{,}570}100 = 13.88 \text{ per cent.}$$

This checks well enough with the 15 per cent. regulation assumed.

Efficiency

$$\eta = \frac{1{,}667{,}000}{1{,}667{,}000+(118.4)^2 13.66} = 1{,}667{,}000/1{,}858{,}000 \text{ or } 89.6 \text{ per cent.}$$

16. Use of complex quantity. Analytical solutions of problems involving vector quantities may be made by resolving each vector into two components, one along a horizontal or X axis, called the axis of reals, and the other along the vertical, or Y axis, called the axis of imaginaries. The latter component is preceded by $j = (\sqrt{-1})$ with + or − sign according to whether it leads or lags with respect to the positive real component. lag being measured in a clockwise direction.

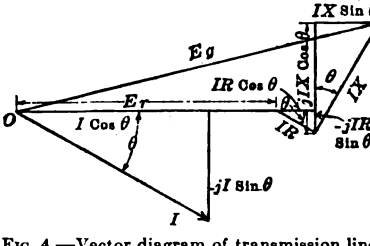


FIG. 4.—Vector diagram of transmission line using complex quantities.

Fig. 3 may be treated by this method, as shown in Fig. 4, where each quantity is resolved into a real component along E_r, the axis of reals, and into a quadrature component along the axis of imaginaries, at right angles to E_r.

$$E_g = e+je' = E_r + I\ (\cos\theta - j\sin\theta)\ (R+jX) \qquad (12)$$

Each quantity represented in Fig. 4 is obtained by performing the mul-

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tiplication in (12). (The effect of each component of current is treated as if the other did not exist.) The plus sign is used when I leads E_r. The absolute value of E_g is given by $\sqrt{e^2+e'^2}$.

17. Example of analytical solution of three-phase line using complex quantity. Consider the problem of Par. **15.**

Here $E_g = 16{,}570 + 118.4(0.850 - j0.527)(13.66 + j14.68) = 16{,}570 + 1{,}374 + j1475 - j852 + 916 = 18{,}860 + j623$. Hence $E_g = \sqrt{18{,}860^2 + 623^2} = 18{,}870$.

$$\text{Regulation} = \frac{18{,}870 - 16{,}570}{16{,}570} 100 = 13.88 \text{ per cent., as before.}$$

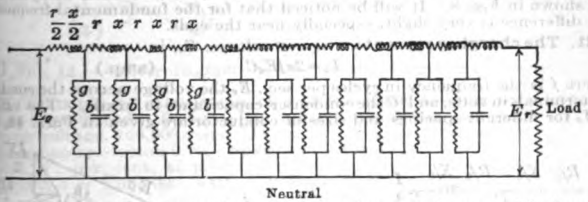


FIG. 5.—Equivalent transmission line showing capacitance and leakance.

18. Line capacitance has negligible effect on short or low-voltage lines, and, for such lines, may be neglected. On the longer lines of higher voltage, the line charging current has a marked influence on the line regulation, and hence must be considered in the design of the line.

On longer lines of higher voltage the charging current must be taken into consideration. It leads the voltage by 90 deg., and because of the line reactance, it tends to produce a *rise* in voltage from the sending end to the receiving end. With an in-phase or with a lagging current the effect of the charging current is to improve the line regulation and the generator power-factor. If the receiving end is open-circuited, the voltage at the receiving end becomes greater in magnitude than the voltage at the sending end.

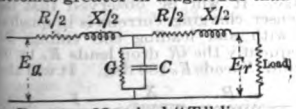


FIG. 6.—Nominal "T" line.

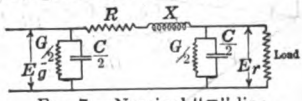


FIG. 7.—Nominal "π" line.

19. Nominal "T" line and nominal "Π" line. A transmission line at normal frequencies may be represented by a single conductor having a uniform linear resistance ($R = r + r + r \ldots$), reactance ($X = x + x + x \ldots$), leakance ($G = g + g + \ldots$) and capactive susceptance ($B = b + b + \ldots$) in parallel between the line and neutral (see Fig. 5). The exact analytical placement of such a line is rather complicated, and for practical purposes the shunt admittance consisting of the leakance G and susceptance B may be considered as concentrated at the centre of the line (Fig. 6), or in two admittances, each of one-half the total line admittance, placed at opposite ends of the line (Fig. 7). The former is termed a nominal T and the latter a nominal π, or a split condenser. In the former case the entire charging current flows over half the line and in the latter case one-half the charging

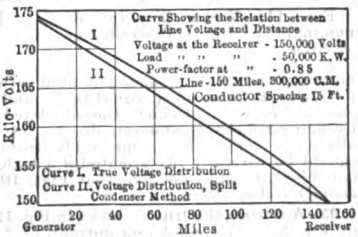


FIG. 8.—Voltage drop in line.

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current flows over the entire line. The leakage current can usually be neglected. Where the corona and insulator losses are not negligible their effect may be included. If the transformers are to be included with the line, their equivalent single-phase resistance and leakage reactance must be added to the line resistance and reactance respectively; the energy component of the no-load current must be added to the line leakage-current and the quadrature component or magnetising current must be subtracted from the line charging-current.

20. Voltage distribution. The true voltage distribution and the approximate voltage distribution for a 150-mile, 150,000-volt, 60-cycle line are shown in Fig. 8. It will be noticed that for the fundamental frequency the difference is very slight, especially near the ends.

21. The charging current for a given voltage, E_s, is

$$I_c = 2\pi f E_s C \quad \text{(amp.)} \qquad (14)$$

where f is the frequency in cycles per sec., E_s the voltage across the condenser terminals in volts, and C the condenser capacitance in farads. The values of I_c for different spacings and sizes of conductor are given in Pars. 44, 45.

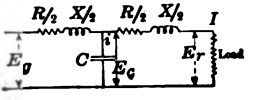


FIG. 9.—Nominal "T" line.

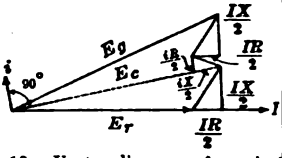


FIG. 10.—Vector diagram of nominal "T" line. Power-factor = 1.0.

22. A nominal "T" line is shown in Fig. 9, and Fig. 10 shows the vector relations in the circuit for unity power-factor load. Fig. 11 gives the vector diagram when the load current lags by an angle θ with respect to the load voltage. It will be observed that the condenser charging current is in quadrature with and leading the voltage E_r, consequently the iR drop leads E_r by 90 deg. and iX leads E_c 180 deg. It will also

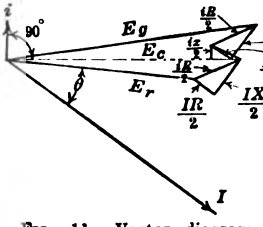


FIG. 11.—Vector diagram of nominal "T" line. Power-factor = cos θ.

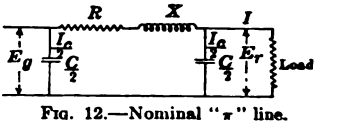


FIG. 12.—Nominal "π" line.

be noted that E_s is at some potential between E_g and by E_r but for practical purposes, E_s is assumed equal to E_r, and no appreciable error results in the charging current. In fact, the calculated charging current may be in error by many times this amount, due to the fact that the e.m.f. wave of the alternator may differ appreciably from a sine wave. This last factor should be carefully investigated if a high degree of accuracy is desired. It is evident, from inspection, that Figs. 10 and 11, are not capable of simple geometrical solution.

23. A nominal π line is shown in Fig. 12, and the vector diagram is shown in Fig. 13. The condenser current $I_c/2$ leads E_r by an angle of 90 deg., and is readily combined with the current I to form the total current I_s.

$$I_s = \sqrt{(I\cos\theta)^2 + (I\sin\theta - I_c/2)^2} \qquad (15)$$

$$\cos\theta_s = I\cos\theta/I_s \qquad (16)$$

where $\cos\theta$ and $\cos\theta_s$ are the load and resultant power-factors, respectively,

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Sin θ becomes negative, when I leads E_r, but the square of the second term under the radical still remains positive.

The problem is then treated by the method employed in Pars. 12 to 17.

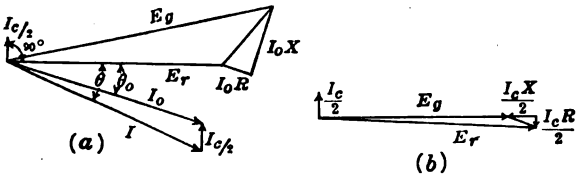


FIG. 13.—Vector diagram showing effect of line charging current.

24. Example of calculation of a three-phase system with capacitance considered. Power to be transmitted, 50,000 kw. Substation or receiver voltage, 140,000 volts. Distance, 120 miles. Frequency, 60 cycles. Full-load power-factor, 0.90. Spacing of wires, 14 ft. Allowable power loss in line, 10 per cent. of power at receiver. Power lost in each wire = 5,000,000/3 = 1,667,000 watts. Voltage to neutral (receiver) = 140,000 $/\sqrt{3}$ = 80,830. Load current per wire = $\frac{5{,}000{,}000}{3 \times 80{,}830 \times 0.90}$ = 229.2 amp. Resistance per wire = 1,667,000/(229.2)² = 31.75 ohms. Resistance per mile = 31.75/120 = 0.2646 ohm.

From Table 40, 0000 copper or 336,400 cir. mil. aluminum have the nearest resistance, 0.272 ohm per mile. Use aluminum on account of its greater diameter. The total resistance is 0.272 × 120 = 32.64 ohms. From Table 43, by interpolation, the reactance per mile of wire = 0.795 ohm. Total reactance = 0.795 × 120 = 95.40 ohms. From Table 45 the charging current per mile per 100,000 volts is found to be 0.541 amp. Total charging current = $\frac{80{,}830 \times 0.541 \times 120}{100{,}000}$ = 42.57 amp. Charging current at the receiving end of the line $I_c/2 = 52.47/2 = 26.24$ amp. From Eqs. 15 and 16, Par. 23, $I_o = \sqrt{(229.2 \times 0.90)^2 + (229.2 \times 0.4358 - 26.24)^2} =$ 219.0 amp.

$$\cos \theta_o = (229.2 \times 0.90)/219 = 0.9420$$

$IR = 219.0 \times 32.64 = 7{,}148$ volts. $IX = 219.0 \times 95.40 = 20{,}890$ volts. By equation (8)

$$E_g = 80{,}830 \sqrt{\left(0.9420 + \frac{7{,}148}{80{,}830}\right)^2 + \left(0.3355 + \frac{20{,}890}{80{,}380}\right)^2} = 96{,}200 \text{ volts.}$$

When the receiver load is removed, the substation voltage will rise, due to the line charging current flowing through the inductance of the line. On open circuit from (b) Fig. 13, E_r will be:

$$E_r = \sqrt{E_g^2 - \left(\frac{I_c}{2}R\right)^2} + \frac{I_c}{2}X \qquad (17)$$

The $\frac{I_c}{2}R$ term is negligible. $E_r = 96{,}200 + (26.24 \times 95.40) = 96{,}200 + 2{,}500 =$ 98,700 volts.

Regulation = $\frac{98{,}700 - 80{,}830}{80{,}830}$ or 22.10 per cent. Efficiency = $50{,}000 \times 10^3 /$ $[50{,}000 \times 10^3 + (3 \times \overline{219.0}^2 \times 32.64)]$ or 91.4 per cent.

25. The analytical or complex solution of a nominal π line having appreciable capacitance may be obtained by adding the voltage drop due to the load current and to one-half the total line charging current (passing through the line impedance) to the receiver voltage.

$$E_g = e + je' = E_r + I(\cos\theta - j\sin\theta)(R + jX) + \frac{jI_c}{2}(R + jX) \qquad (18)$$

where E_g = the generator voltage from phase wire to neutral; E_r = the receiver voltage from wire to neutral; I = the load current; θ = the phase angle of

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the load; R = the resistance per wire; X = the reactance per wire; and I_c = the total charging current. The geometrical position of each quantity is shown in Fig. 14.

This diagram determines the effect upon the generator voltage of different load conditions at the receiver, the receiver voltage being kept constant.

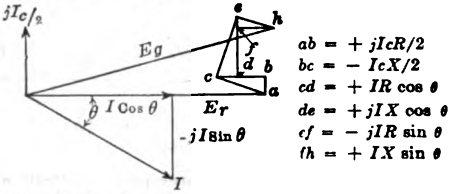


FIG. 14.—Vector diagram of line using complex quantities.

26. Constant load and variable power-factor. Since the receiver voltage is assumed constant, triangle abc (Fig. 15) will not change. Triangle cde and efh are similar. Triangle cde will not change, since $I \cos \theta$ is fixed. $eh/ce = fh/de = (IX \sin \theta)/(IX \cos \theta) = \tan \theta$. $I = P/(E_r \cos \theta)$ or $I \sin \theta = P \tan \theta / E_r = Peh/E_r ce$. As ce, P and E_r are fixed, $I \sin \theta$ varies as $\tan \theta$. Therefore the point h must move along eh, toward h' if the lag of the current increases and toward e if the lead of the current increases, and eh must be proportional to $\tan \theta$.

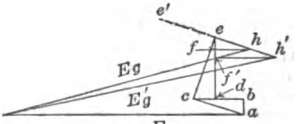


FIG. 15.—Constant load, variable power-factor.

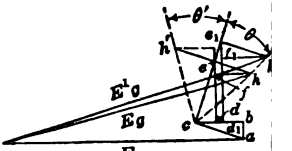


FIG. 16.—Variable load, constant power-factor.

27. Variable load and constant power-factor. (Fig. 16). $ef/cd = (IR \sin \theta)/(IR \cos \theta) = \tan \theta$.

Since cde and efh are similar triangles, $ef/cd = eh/ce = \tan \theta$.

Therefore, angle $ech = \theta$, which is constant, and h must always lie on ch.

Since cd and de are both proportional to I, e will move along ce and d will always be perpendicular to ce. θ' shows the construction for a leading current.

28. Constant voltage maintained at receiver by use of synchronous apparatus. The generator voltage, assumed constant, will move along arc h_2h_1 (Fig. 17). The length ce_1 is equal to $I \cos \theta$ $(R + jX)$ at no-load. It is then proportional to the power taken by the synchronous apparatus and e_1 will move along ce_2 with increase of load. e_1h_1 is equal to $I \sin \theta$ $(R + jX)$, hence is proportional to the quadrature component of the current. In order to maintain constant receiver voltage, with increase of load, eh must decrease until at e_2 it is equal to zero and this point must correspond to unity power-factor. With further increase of load e_1h_1 reverses and the current leads as at e_3h_3. This condition may be obtained by compounding or by changing the excitation of the synchronous apparatus, either automatically, or by hand.

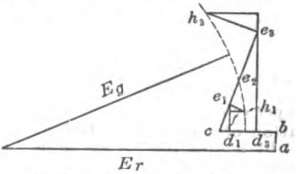


FIG. 17.—Constant voltage at receiver.

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29. Example of analytical solution of nominal π line using complex quantity. Consider problem of Par. **24**, see Par. **25**, $E_g = 80{,}830 + 229.2(0.90 - j0.4358)\ (32.64 + j95.40) + (j52.47/2)\ (32.64 + j95.40) = 80{,}830 + 6{,}735 + j19{,}680 - j3{,}260 - j9{,}540 + j857 - 2{,}500 = 94{,}600 + j17{,}280$ or 96,200 volts (absolute).

At no-load $96{,}200 = E_r + (j52.47/2)(32.64 + j95.40)$.

The quadrature resistance drop is negligible. Hence $E_r = 96{,}200 + (26.24 \times 95.40) = 98{,}700$ volts, which checks with the result obtained in Par. **24**.

30. Exact methods of calculating regulation may be desirable if the line is long, the line voltage high or if harmonics be taken into consideration. Such methods involve the distributed nature of the line admittance. Formulas for such lines expressed in circular trignometric functions are very complicated. If hyperbolic functions* are used the relations become quite simple.

31. The general equations of the transmission line in hyperbolic functions are:

$$E_1 = E_2 \cosh \sqrt{ZY} \pm I_2 \sqrt{Z/Y} \sinh \sqrt{ZY} \tag{19}$$

$$I_1 = I_2 \cosh \sqrt{ZY} \pm (E_2 / \sqrt{Z/Y}) \sinh \sqrt{ZY} \tag{20}$$

where E_1 and E_2 are the respective voltages from phase wire to neutral at the sending and receiving ends of the line if the positive sign is taken. If the negative sign is taken E_1 and E_2 are the respective voltages at the receiving and sending ends of the line. The same relation holds true for the currents, I_1 and I_2. Ordinarily the positive sign is used, as the receiver voltage and load current are generally known.

Z is the impedance per wire $= R + jX$, and Y is the admittance from phase wire to neutral $= G + jB$, though the leakage G is usually negligible in an actual line.

Expanding the cosh and sinh terms in a converging series by Maclaurin's Theorem, and neglecting the terms after the second, the following expressions are obtained:

$$E_1 = E_2\ (1 + ZY/2) \pm ZI_2(1 + ZY/6) \tag{21}$$

$$I_1 = I_2\ (1 + ZY/2) \pm YE_2(1 + ZY/6) \tag{22}$$

32. Example of calculation using general equation Par. 31. Consider again the problem of Par. **24**.

$E_1 = E_g =$ generator voltage, $E_2 = E_r =$ receiver voltage $= 80{,}830$ volts. $Z = R + jX = 32.64 + j95.40$, $Y = G + jB = 0 + j6.49 \times 10^{-4}$, $I_1 =$ generator current, to be determined. $I_2 = I(\cos\theta - j \sin\theta) = 229.2(0.900 - j0.4358) = 206.3 - j99.88$. Applying equation (21)

$$E_1 = 80{,}830\left[1 + \frac{(32.64 + j95.40)(j6.49 \times 10^{-4})}{2}\right] + (32.64 + j95.40)(206.3 - j99.88)\left[1 + \frac{(32.64 + j95.40)(j6.49 \times 10^{-4})}{6}\right]$$

$$= 94{,}340 + j17{,}164 = 95{,}900 \text{ volts.} \quad \text{(Absolute)}$$

The no-load receiver voltage and the regulation may be found as in Par. **24**, Eq. 17.

Likewise I_g is readily determined.

$$I_g = (206.3 - j99.88)\left[1 + \frac{(32.64 + j95.40)(j6.49 \times 10^{-4})}{2}\right]$$

$$+ (j6.49 \times 10^{-4})(80{,}830)\left[1 + \frac{(32.64 + j95.40)(6.49 \times 10^{-4})}{6}\right]$$

$$= 201.8 - j12.70 = 206.2 \text{ amp.} \quad \text{(absolute)}$$

Graphic diagrams or charts are available for giving the vector values of $\sinh(\sqrt{ZY})$ and $\cosh(\sqrt{ZY})$ in (19) and (20) without having to compute the expansions contained in (21) and (22). See Bibliography 13 and 14.

* Kennelly, A. E. "The Application of Hyperbolic Functions to Electrical Engineering Problems." McGraw-Hill Book Co. Inc., 1916.
"Artificial Electric Lines." McGraw-Hill Book Co. Inc., 1917.

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33. Equivalent "T" line and equivalent "π" line. A simple or nominal T-line, Fig. 18, in which the entire line admittance is considered as being concentrated at the center, may be converted into an *equivalent* T-line by multiplying each linear impedance $Z/2$ by $\tanh\frac{\theta}{2}/\frac{\theta}{2}$, where $\theta = \sqrt{ZY}$ and by multiplying the total admittance Y by $\sinh\theta/\theta$. If the *equivalent* constants Z' and Y' be used in computations, the line as far as the terminals A and B and beyond are concerned will behave in the steady state as if the line admittance were uniformly distributed. Tables of the conversion factors $\sinh\theta/\theta$ and $\tanh\theta/\theta$ are given in Par. 46 and 47.

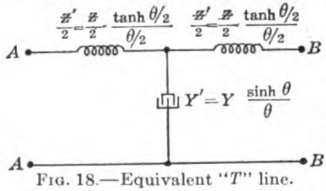


FIG. 18.—Equivalent "T" line.

Fig. 19 shows a nominal Π line of linear impedance $Z=R+jX$, and total capacitive admittance, $Y/2$, at each end of the line. If $R+jX$ be multiplied by $(\sinh\theta)/\theta$, and $Y/2$ by $(\tanh\theta/2)/(\theta/2)$, where $\theta=\sqrt{ZY}$, the line as far as the ends (and beyond) are concerned will behave in the steady state exactly as if the line constants were uniformly distributed. The new line is then considered an *equivalent* π-line and its characteristics are then calculated by the method of either Par. **24** or **25**.

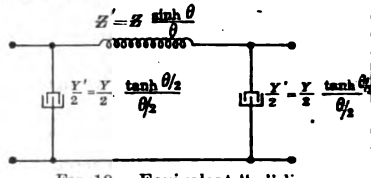


FIG. 19.—Equivalent "π" line.

34. The relation of potential and current along a line can be expressed simply by hyperbolic functions. A line AB, Fig. 20, has a uniform total conductor impedance Z, a uniform total admittance Y, and a load at B of Z_1 ohms impedance. The vector hyperbolic angle of the line is $\theta=\sqrt{ZY}$. The hyperbolic angle of the line, including the effect of the load impedance Z_1, is $\theta'=\theta+\theta_1$, where $\theta_1=\tanh^{-1}\frac{Z_1}{\sqrt{Z/Y}}$.

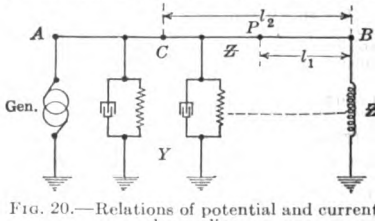


FIG. 20.—Relations of potential and current along a line.

The hyperbolic angle of the line to any point P, l_1 units distant from B, is $\delta_p=l_1\alpha+\theta_1$, where $\alpha=\sqrt{zy}$, the propagation constant per unit length of line: (z is the impedance per *unit length* of line, and y the admittance per *unit length* of line). Likewise, the hyperbolic angle δ_c to any point C, l_2 units distant from B is $\delta_c=l_2\alpha+\theta_1$.

The relations of the voltages, currents, impedances, and admittances are as follows:

$$\frac{V_p}{V_c}=\frac{\sinh\delta_p}{\sinh\delta_c},\quad \frac{I_p}{I_c}=\frac{\cosh\delta_p}{\cosh\delta_c},\quad \frac{Z_p}{Z_c}=\frac{\tanh\delta_p}{\tanh\delta_c},\quad \frac{Y_p}{Y_c}=\frac{\coth\delta_p}{\coth\delta_c}$$

(See Par. 50 also.

35. Charts and diagrams, when drawn to a sufficiently large scale, are convenient for determining the electrical characteristics of transmission lines. It is essential, however, that the precision and limitations of the curves be known. Even if great refinement of calculation be desired, such diagrams are useful for checking computed results. In a handbook it is not possible to present the diagrams on a sufficiently large scale. It has seemed wise to explain their construction, with data, their methods of use and also to refer to the original articles in which they are described.

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36. The Perrine-Baum* regulation diagram, originally proposed by F. A. C. Perrine and F. G. Baum and based on the diagram shown in Fig. 13, forms a convenient method of studying transmission line regulation. To facilitate use of the diagram, the effect of phase displacement is taken into account by rotating the impedance triangle BDC.

The load current is proportional to $1/\cos\theta = \sec\theta$, and the impedance drop, being directly proportional to the load current, is obtained by laying off the phase angle as shown in Fig. 21*a*. If BD is the impedance drop for unity

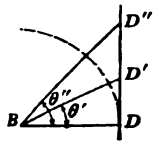


FIG. 21*a*.

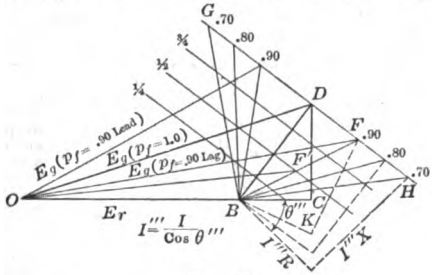


FIG. 21*b*.

FIG. 21.—Perrine-Baum diagram.

power-factor, then $BD' = BD \sec\theta'$ is the impedance drop for the power-factor $\cos\theta'$, and $BD'' = BD \sec\theta''$ is the drop for the power-factor $\cos\theta''$, etc.; that is, the impedance-drop vector always terminates on a straight line, drawn at right angles to the drop BD for unity power-factor.

The diagram is shown in Fig. 21*b*, in which the line capacitance is neglected. Its use will be clear from the following example:

37. Example of calculation using Perrine-Baum regulation diagram. Assume 1,000 kw. to be transmitted to a substation at 0.90 power-factor, lagging, the voltage at the substation to be maintained constant at 10,000 volts. The line has a resistance of 8 ohms and an inductive reactance of 15 ohms. The line capacitance is neglected. With unity power-factor, the line current is $1{,}000{,}000/10{,}000 = 100$ amp. Referring to Fig. 21(*b*), lay off $OB = 10{,}000$ volts, $BC = 100 \times 8 = 800$ volts, and $CD = 100 \times 15 = 1{,}500$ volts. If the power-factor were unity, OD would be the voltage at the generating station. To determine the generator voltage for 0.90 power-factor, lagging, draw GH perpendicular to BD and lay off to the right of BD an angle, DBF, whose cosine is equal to 0.90. The line impedance drop will be represented by BF, hence OF shows the voltage at the generating station for this power-factor. For any other power-factor, $\cos\theta$, lay off the angle θ to the right of BD for lagging currents, and to the left of BD for leading currents. The voltage at the generating station will be determined by the line joining O with the terminal of the line impedance drop for the given $\cos\theta$. For other loads, hence other values of line current, BD is divided into proportional parts, and lines parallel to GH are drawn as shown. For example, the voltage at the generating station at one half-load and with a power-factor of 0.9 (lagging), is represented in the diagram by the line OF'.

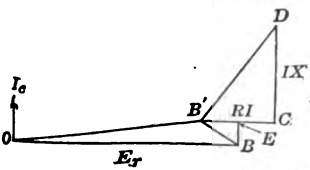


FIG. 22.—Effect of charging current.

* Bibliography 1.

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Line capacitance is taken into account by assuming a constant load voltage; from this assumption the charging current is calculated, taking this current as in quadrature, leading, with respect to the receiving voltage, if the power-factor is unity. The drop due to the charging current in one-half the line impedance is laid off from the receiving voltage vector as shown in triangle BEB′, Fig. 22 (also see Fig. 14), and the usual impedance triangle B′CD constructed from B' the end of the vector representing the impedance drop due to the charging current. The usual diagram, such as is shown in Fig. 21, is then constructed upon the impedance triangle. It will be noted that this method assumes that the charging current is fixed in phase and magnitude, which, though not strictly accurate, is sufficiently so for most purposes in overhead line calculation, except for lines of great length.

38. The Mershon* diagram. If the e.m.f. diagram shown in Fig. 3 is rotated about O as a centre through an angle θ, where cos θ is the power-factor, and all e.m.fs. are expressed in per cent. of the voltage generated at unity power-factor, the line drop, neglecting the charging current, being measured along a radius with center O, then a simple diagram for determining regulation may be developed. Such a diagram is constructed by drawing a series of concentric circles *ab*, *cd*, etc. (Fig. 23) upon a coordinate system of equal squares; a side of one of these squares is equal to the difference in radii between any two consecutive circles. The radius OB is taken at 100 per cent. and the coordinate spaces may conveniently represent intervals of 5 per cent. The power-factor is cos θ and is numerically equal to the projection of OB' upon the horizontal axis. Having definite line constants, and with a load of given power-factor, the resistance and the reactance voltage drops are calculated in per cent. of the receiver voltage. Starting at the foot of the ordinate representing the load power-factor, follow this ordinate up to its intersection with the first circle, which is the locus of the point B of the impedance triangle. From this last point lay off on the coordinates the impedance triangle. The circle upon which the apex D lies will give the per cent. drop directly. The diagram constructed to scale is given in Sec. 12, Fig. 11, and the table of Sec. 12, Par. **31** is calculated for use with it.

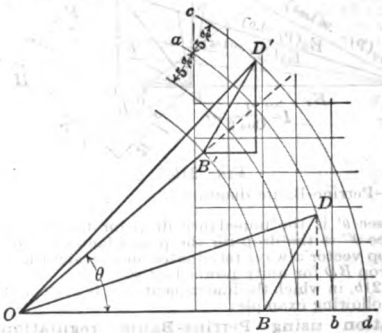


FIG. 23.—Mershon diagram.

An example illustrating the use of the Mershon diagram is given in Sec. 12, Par. **35**.

39. The Dwight Chart,† shown in Fig. 24, gives a simple method of determining regulation. With the original chart the precision is stated to be better than one-half of one per cent. but on account of the reduction in size from the original, the precision obtainable with Fig. 24 is slightly less than this. The directions for use accompany the diagram.

40. Resistance of transmission-line conductors will be found in the tables given in Sec. 4, under the appropriate sub-heads.

TABLES OF INDUCTIVE REACTANCE AND CHARGING CURRENT

41. The inductance and capacitance of transmission lines may be calculated from the formulas given in Sec. 2. The values of inductive reactance and charging current for wires of standard size, with usual spacing up to 20 ft., at both 25 cycles and 60 cycles, are given in the tables in Par. **42–45**. Nineteen strands are assumed for cables of 750,000 to 350,000 cir. mils

* Mershon, Ralph D. "Drop in Alternating Current Lines." *The American Electrician*, Vol. IX (1899), p. 220.

† Dwight, H. B. "Transmission Line Formulas." D. Van Nostrand Co.

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inclusive. Seven strands are assumed in the smaller sizes. The effect is the different number of strands on the reactance and charging current is very small.

Tables 46 and 47 give the hyperbolic correction factors $\frac{\sinh \theta}{\theta}$ and $\frac{\tanh \theta}{\theta}$.

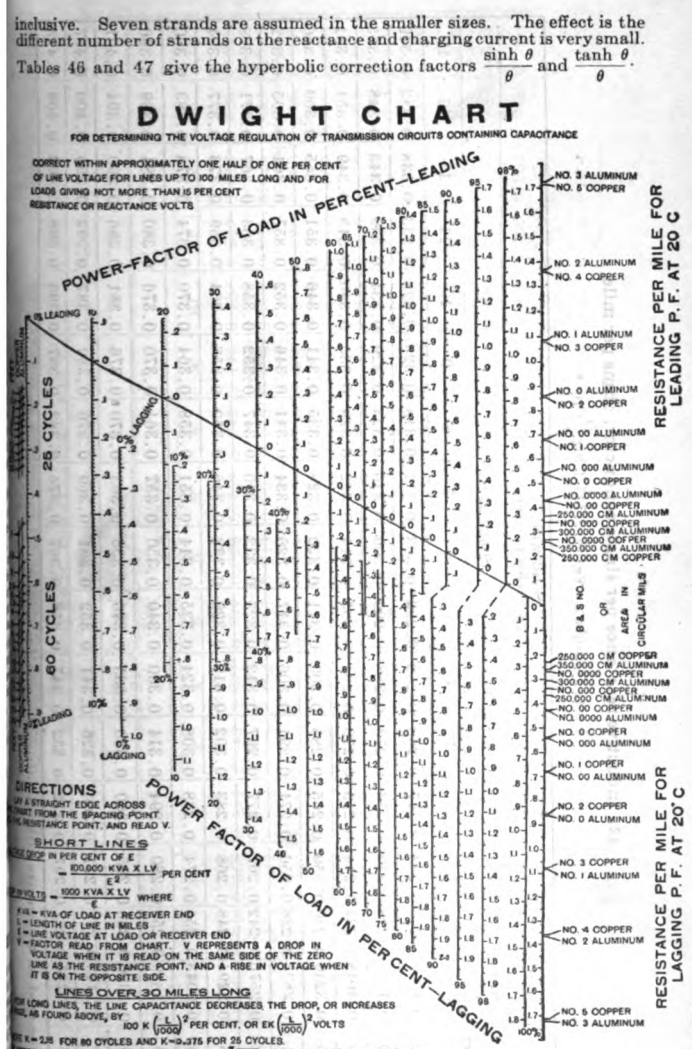
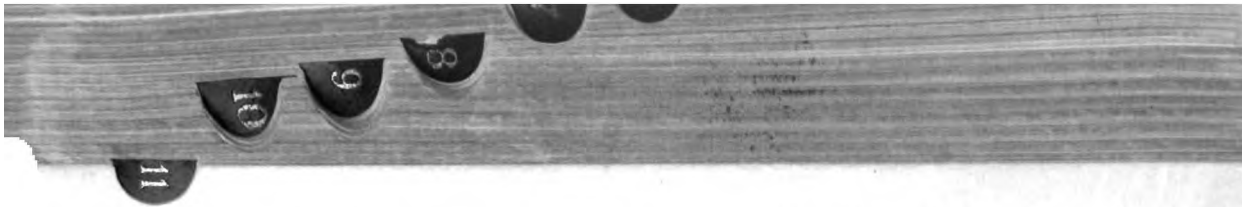


FIG. 24.

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42. Inductive reactance per single conductor, ohms per mile

From formula $x = 2\pi f(80 + 741.1 \log \frac{D}{r}) 10^{-6}$

Size A.W.G.	Outside diam. in.	Solid wire 25 cycles per sec. Spacing, ft. 1	1.5	2	3	4	5	6	7	8	9	10	11	12	13	15
0000	0.4600	0.212	0.233	0.247	0.268	0.282	0.293	0.303	0.311	0.318	0.323	0.328	0.333	0.338	0.342	0.349
000	0.4096	0.218	0.239	0.253	0.273	0.288	0.299	0.309	0.316	0.323	0.329	0.334	0.339	0.343	0.348	0.355
00	0.3648	0.224	0.244	0.259	0.279	0.294	0.305	0.314	0.322	0.329	0.335	0.340	0.345	0.349	0.354	0.361
0	0.3249	0.230	0.250	0.265	0.285	0.300	0.311	0.320	0.328	0.335	0.341	0.346	0.351	0.355	0.360	0.366
1	0.2893	0.236	0.256	0.271	0.291	0.306	0.317	0.326	0.334	0.341	0.346	0.352	0.357	0.361	0.365	0.372
2	0.2576	0.242	0.262	0.277	0.297	0.312	0.323	0.332	0.340	0.347	0.352	0.358	0.363	0.367	0.371	0.378
3	0.2294	0.248	0.268	0.283	0.302	0.318	0.329	0.338	0.346	0.352	0.358	0.364	0.369	0.373	0.377	0.384
4	0.2043	0.253	0.274	0.288	0.308	0.324	0.335	0.344	0.351	0.358	0.364	0.370	0.374	0.378	0.383	0.390
5	0.1819	0.259	0.280	0.294	0.314	0.330	0.340	0.350	0.357	0.364	0.370	0.376	0.380	0.384	0.389	0.396
6	0.1620	0.265	0.285	0.300	0.320	0.335	0.346	0.356	0.363	0.370	0.376	0.381	0.386	0.390	0.394	0.401
7	0.1443	0.271	0.291	0.306	0.326	0.341	0.352	0.361	0.369	0.376	0.382	0.387	0.392	0.396	0.400	0.407
8	0.1285	0.277	0.297	0.312	0.332	0.347	0.358	0.367	0.375	0.382	0.387	0.393	0.398	0.402	0.406	0.413

To be used on all circuits with quantities measured *to neutral*.

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42. Inductive reactance per single conductor, ohms per mile

From formula $x = 2\pi f(80 + 741.1 \log \frac{D}{r}) 10^{-6}$

Size A.W.G.	Outside diam. in.	Solid wire 60 cycles per sec. Spacing, ft. 1	1.5	2	3	4	5	6	7	8	9	10	11	12	13	15
0000	0.4600	0.510	0.558	0.594	0.642	0.677	0.704	0.726	0.746	0.762	0.776	0.788	0.800	0.810	0.820	0.838
000	0.4096	0.524	0.572	0.608	0.656	0.692	0.718	0.740	0.760	0.776	0.790	0.802	0.814	0.824	0.834	0.852
00	0.3648	0.538	0.586	0.622	0.670	0.706	0.732	0.754	0.774	0.790	0.804	0.816	0.828	0.838	0.848	0.866
0	0.3249	0.552	0.600	0.636	0.684	0.720	0.746	0.768	0.788	0.804	0.818	0.830	0.842	0.852	0.862	0.880
1	0.2893	0.566	0.614	0.649	0.698	0.734	0.760	0.782	0.802	0.818	0.832	0.844	0.856	0.866	0.876	0.894
2	0.2576	0.580	0.628	0.664	0.712	0.748	0.774	0.796	0.816	0.832	0.846	0.858	0.870	0.880	0.890	0.908
3	0.2294	0.594	0.642	0.678	0.726	0.762	0.788	0.810	0.829	0.846	0.860	0.872	0.884	0.894	0.904	0.922
4	0.2043	0.608	0.657	0.692	0.740	0.776	0.803	0.824	0.843	0.860	0.874	0.886	0.898	0.908	0.918	0.936
5	0.1819	0.622	0.671	0.706	0.754	0.790	0.817	0.838	0.858	0.874	0.888	0.900	0.912	0.922	0.932	0.950
6	0.1620	0.636	0.684	0.720	0.768	0.804	0.831	0.853	0.872	0.888	0.902	0.915	0.926	0.936	0.946	0.964
7	0.1443	0.650	0.698	0.734	0.782	0.818	0.845	0.867	0.886	0.902	0.916	0.929	0.940	0.950	0.960	0.978
8	0.1285	0.663	0.712	0.748	0.796	0.832	0.859	0.880	0.900	0.916	0.929	0.943	0.954	0.964	0.974	0.992

D = distance between conductor centers; r = conductor radius.
To be used on all circuits with quantities measured *to neutral*.

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43. Inductive reactance per single conductor, ohms per mile

Stranded conductor
25 cycles per sec.

Size cir. mils A. W. G.	Outside diam. in.	Spacing, ft. 2	4	5	6	7	8	9	10	11	12	13	14	15	17.5	20
750,000	0.993	0.212	0.247	0.258	0.268	0.275	0.282	0.288	0.293	0.298	0.303	0.307	0.310	0.314	0.321	0.329
600,000	0.889	0.218	0.253	0.264	0.273	0.281	0.288	0.293	0.299	0.304	0.308	0.312	0.316	0.319	0.327	0.334
500,000	0.8111	0.223	0.258	0.269	0.279	0.287	0.293	0.299	0.304	0.309	0.313	0.317	0.320	0.324	0.332	0.339
450,000	0.7695	0.226	0.261	0.272	0.281	0.289	0.296	0.301	0.307	0.311	0.316	0.320	0.324	0.327	0.335	0.342
400,000	0.7255	0.229	0.264	0.275	0.284	0.292	0.299	0.305	0.310	0.315	0.319	0.323	0.327	0.330	0.338	0.344
350,000	0.6786	0.232	0.267	0.278	0.288	0.296	0.302	0.308	0.313	0.318	0.322	0.326	0.330	0.334	0.341	0.347
300,000	0.6211	0.236	0.271	0.284	0.291	0.299	0.306	0.311	0.317	0.321	0.326	0.330	0.334	0.337	0.345	0.352
250,000	0.5669	0.241	0.275	0.287	0.296	0.304	0.310	0.316	0.321	0.326	0.331	0.335	0.338	0.342	0.350	0.357
0000	0.5216	0.245	0.280	0.291	0.300	0.308	0.315	0.320	0.326	0.330	0.335	0.339	0.343	0.346	0.354	0.361
000	0.4645	0.251	0.286	0.297	0.306	0.314	0.320	0.326	0.331	0.336	0.341	0.345	0.348	0.352	0.360	0.367
00	0.4137	0.257	0.291	0.302	0.312	0.320	0.326	0.332	0.337	0.342	0.347	0.350	0.354	0.358	0.366	0.373
0	0.3683	0.262	0.297	0.308	0.318	0.326	0.332	0.338	0.343	0.348	0.353	0.356	0.360	0.364	0.371	0.378
1	0.3280	0.268	0.303	0.314	0.324	0.331	0.338	0.344	0.349	0.354	0.358	0.362	0.366	0.370	0.377	0.384
2	0.2921	0.275	0.309	0.320	0.330	0.338	0.344	0.350	0.355	0.360	0.365	0.368	0.372	0.376	0.384	0.390
3	0.2601	0.280	0.315	0.326	0.336	0.344	0.350	0.356	0.361	0.366	0.370	0.374	0.378	0.382	0.389	0.396
4	0.2317	0.286	0.321	0.332	0.342	0.349	0.356	0.361	0.367	0.372	0.376	0.380	0.384	0.387	0.395	0.401

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43. Inductive reactance per single conductor, ohms per

Stranded conductor
60 cycles per sec.

Size cir. mils A. W. G.	Outside diam. in.	Spacing, ft.														
		2	4	5	6	7	8	9	10	11	12	13	14	15	17.5	20
750,000	0.993	0.508	0.593	0.620	0.642	0.660	0.677	0.692	0.704	0.716	0.727	0.736	0.745	0.754	0.772	0.789
600,000	0.889	0.523	0.606	0.634	0.656	0.674	0.691	0.704	0.718	0.730	0.740	0.750	0.759	0.767	0.786	0.802
500,000	0.8111	0.535	0.619	0.647	0.669	0.688	0.703	0.718	0.730	0.742	0.752	0.762	0.771	0.779	0.797	0.813
450,000	0.7695	0.541	0.625	0.653	0.675	0.693	0.709	0.724	0.736	0.748	0.758	0.767	0.776	0.784	0.803	0.820
400,000	0.7255	0.548	0.632	0.660	0.682	0.700	0.716	0.731	0.743	0.755	0.765	0.775	0.784	0.793	0.811	0.827
350,000	0.6786	0.556	0.640	0.668	0.690	0.708	0.724	0.739	0.751	0.763	0.774	0.783	0.792	0.801	0.820	0.835
300,000	0.6211	0.566	0.650	0.677	0.699	0.718	0.734	0.748	0.760	0.772	0.783	0.792	0.801	0.810	0.831	0.846
250,000	0.5669	0.577	0.661	0.688	0.711	0.729	0.745	0.759	0.772	0.783	0.794	0.804	0.812	0.821	0.840	0.857
0000	0.5216	0.587	0.672	0.698	0.722	0.739	0.755	0.770	0.782	0.793	0.804	0.814	0.822	0.831	0.850	0.866
000	0.4645	0.601	0.685	0.713	0.735	0.754	0.769	0.784	0.796	0.808	0.818	0.828	0.836	0.845	0.864	0.881
00	0.4137	0.615	0.699	0.726	0.748	0.767	0.782	0.798	0.810	0.822	0.832	0.842	0.850	0.859	0.878	0.895
0	0.3683	0.629	0.714	0.740	0.762	0.781	0.797	0.812	0.824	0.836	0.846	0.856	0.865	0.874	0.892	0.909
1	0.3280	0.643	0.728	0.755	0.777	0.796	0.812	0.826	0.838	0.850	0.860	0.870	0.879	0.888	0.906	0.922
2	0.2921	0.658	0.742	0.770	0.792	0.810	0.826	0.841	0.853	0.865	0.875	0.885	0.894	0.902	0.922	0.936
3	0.2601	0.672	0.756	0.783	0.806	0.824	0.840	0.854	0.867	0.878	0.889	0.898	0.907	0.916	0.934	0.952
4	0.2317	0.686	0.770	0.798	0.820	0.838	0.854	0.869	0.881	0.893	0.903	0.912	0.922	0.930	0.948	0.964

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44. Charging current per single wire, amperes per mile, per 100,000 volts from phase-wire to neutral

From formula $I = \frac{2\pi f \times 89.42 \times 10^{-9}}{\cosh^{-1}\left(\frac{D}{d}\right)} E = \frac{2\pi f \times 38.83 \times 10^{-9}}{\log_{10}\left(\frac{2D}{d} - \frac{d}{2D}\right)} E$

Solid wire
25 cycles per sec.

Size A.W.G.	Outside diam. in.	Spacing, ft.															
		1	1.5	2	3	4	5	6	7	8	9	10	11	12	13	15
0000	0.4600	0.355	0.322	0.302	0.278	0.263	0.252	0.244	0.238	0.233	0.228	0.224	0.221	0.218	0.215	0.211
000	0.4096	0.345	0.314	0.295	0.272	0.257	0.247	0.240	0.234	0.228	0.224	0.220	0.217	0.214	0.212	0.207
00	0.3648	0.335	0.306	0.288	0.266	0.252	0.242	0.235	0.229	0.224	0.220	0.216	0.213	0.211	0.208	0.204
0	0.3249	0.326	0.298	0.281	0.260	0.247	0.238	0.230	0.225	0.220	0.216	0.213	0.210	0.207	0.204	0.200
1	0.2893	0.318	0.291	0.275	0.255	0.242	0.233	0.226	0.221	0.216	0.212	0.209	0.206	0.203	0.201	0.197
2	0.2576	0.310	0.284	0.269	0.249	0.237	0.229	0.222	0.217	0.212	0.209	0.205	0.203	0.200	0.198	0.194
3	0.2294	0.302	0.278	0.263	0.244	0.233	0.224	0.218	0.213	0.209	0.205	0.202	0.199	0.197	0.195	0.191
4	0.2043	0.295	0.272	0.257	0.240	0.228	0.220	0.215	0.209	0.205	0.202	0.199	0.196	0.194	0.192	0.188
5	0.1819	0.288	0.266	0.252	0.235	0.224	0.216	0.210	0.206	0.202	0.198	0.196	0.193	0.191	0.189	0.185
6	0.1620	0.281	0.260	0.247	0.230	0.220	0.213	0.207	0.202	0.198	0.195	0.192	0.190	0.188	0.186	0.182
7	0.1443	0.275	0.254	0.242	0.226	0.216	0.209	0.203	0.199	0.195	0.192	0.189	0.187	0.185	0.183	0.180
8	0.1285	0.269	0.249	0.237	0.222	0.212	0.205	0.200	0.196	0.192	0.189	0.186	0.184	0.182	0.180	0.177

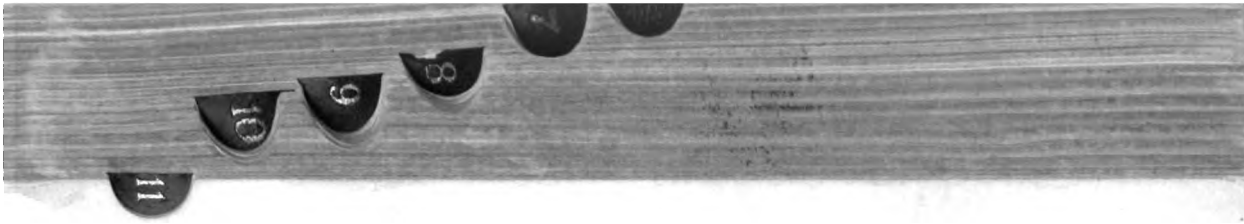
E = volts to neutral; D = distance between wires; d = diameter of wires.

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44. Charging current per single wire, amperes per mile, per 100,000 volts from phase-wire to neutral

Size A.W.G.	Outside diam. in.	Solid wire 60 cycles per sec. Spacing, ft. 1	1.5	2	3	4	5	6	7	8	9	10	11	12	13	15
0000	0.4600	0.852	0.773	0.725	0.667	0.631	0.606	0.587	0.571	0.559	0.548	0.539	0.531	0.523	0.517	0.506
000	0.4096	0.828	0.753	0.708	0.652	0.618	0.593	0.575	0.560	0.548	0.538	0.529	0.521	0.514	0.508	0.497
00	0.3648	0.805	0.734	0.691	0.638	0.605	0.582	0.564	0.550	0.538	0.528	0.519	0.512	0.505	0.499	0.489
0	0.3249	0.783	0.716	0.675	0.624	0.593	0.570	0.553	0.540	0.528	0.519	0.510	0.503	0.497	0.491	0.481
1	0.2893	0.763	0.690	0.660	0.611	0.581	0.559	0.543	0.530	0.519	0.510	0.502	0.495	0.488	0.483	0.473
2	0.2576	0.744	0.682	0.645	0.598	0.569	0.549	0.533	0.520	0.510	0.501	0.493	0.486	0.480	0.475	0.465
3	0.2294	0.725	0.667	0.631	0.586	0.558	0.539	0.523	0.511	0.501	0.492	0.485	0.478	0.472	0.467	0.458
4	0.2043	0.707	0.652	0.618	0.575	0.548	0.529	0.514	0.502	0.492	0.484	0.477	0.470	0.465	0.460	0.451
5	0.1819	0.690	0.638	0.605	0.564	0.538	0.519	0.505	0.494	0.484	0.476	0.469	0.463	0.458	0.453	0.444
6	0.1620	0.674	0.624	0.592	0.553	0.528	0.510	0.497	0.485	0.476	0.468	0.462	0.456	0.450	0.446	0.437
7	0.1443	0.659	0.611	0.580	0.544	0.519	0.501	0.488	0.477	0.469	0.461	0.455	0.449	0.444	0.439	0.431
8	0.1285	0.645	0.598	0.569	0.533	0.510	0.493	0.480	0.470	0.461	0.454	0.448	0.442	0.437	0.432	0.425

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44. Charging current per single wire, amperes per mile, per 100,000 volts from phase-wire to neutral

From formula $I = \dfrac{2\pi f \times 89.42 \times 10^{-9}}{\cosh^{-1}\left(\frac{D}{d}\right)} E = \dfrac{2\pi f \times 38.83 \times 10^{-9}}{\log_{10}\left(\frac{2D}{d} - \frac{d}{2D}\right)} E$

Solid wire
25 cycles per sec.

Size A.W.G.	Outside diam. in.	Spacing, ft.														
		1	1.5	2	3	4	5	6	7	8	9	10	11	12	13	15
0000	0.4600	0.355	0.322	0.302	0.278	0.263	0.252	0.244	0.238	0.233	0.228	0.224	0.221	0.218	0.215	0.211
000	0.4096	0.345	0.314	0.295	0.272	0.257	0.247	0.240	0.234	0.228	0.224	0.220	0.217	0.214	0.212	0.207
00	0.3648	0.335	0.306	0.288	0.266	0.252	0.242	0.235	0.229	0.224	0.220	0.216	0.213	0.211	0.208	0.204
0	0.3249	0.326	0.298	0.281	0.260	0.247	0.238	0.230	0.225	0.220	0.216	0.213	0.210	0.207	0.204	0.200
1	0.2893	0.318	0.291	0.275	0.255	0.242	0.233	0.226	0.221	0.216	0.212	0.209	0.206	0.203	0.201	0.197
2	0.2576	0.310	0.284	0.269	0.249	0.237	0.229	0.222	0.217	0.212	0.209	0.205	0.203	0.200	0.198	0.194
3	0.2294	0.302	0.278	0.263	0.244	0.233	0.224	0.218	0.213	0.209	0.205	0.202	0.199	0.197	0.195	0.191
4	0.2043	0.295	0.272	0.257	0.240	0.228	0.220	0.215	0.209	0.205	0.202	0.199	0.196	0.194	0.192	0.188
5	0.1819	0.288	0.266	0.252	0.235	0.224	0.216	0.210	0.206	0.202	0.198	0.196	0.193	0.191	0.189	0.185
6	0.1620	0.281	0.260	0.247	0.230	0.220	0.213	0.207	0.202	0.198	0.195	0.192	0.190	0.188	0.186	0.182
7	0.1443	0.275	0.254	0.242	0.226	0.216	0.209	0.203	0.199	0.195	0.192	0.189	0.187	0.185	0.183	0.180
8	0.1285	0.269	0.249	0.237	0.222	0.212	0.205	0.200	0.196	0.192	0.189	0.186	0.184	0.182	0.180	0.177

E = volts to neutral; D = distance between wires; d = diameter of wires.

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44. Charging current per single wire, amperes per mile, per 100,000 volts from phase-wire to neutral

Size A.W.G.	Outside diam. in.	Solid wire 60 cycles per sec. Spacing, ft. 1	1.5	2	3	4	5	6	7	8	9	10	11	12	13	15
0000	0.4600	0.852	0.773	0.725	0.667	0.631	0.606	0.587	0.571	0.559	0.548	0.539	0.531	0.523	0.517	0.506
000	0.4096	0.828	0.753	0.708	0.652	0.618	0.593	0.575	0.560	0.548	0.538	0.529	0.521	0.514	0.508	0.497
00	0.3648	0.805	0.734	0.691	0.638	0.605	0.582	0.564	0.550	0.538	0.528	0.519	0.512	0.505	0.499	0.489
0	0.3249	0.783	0.716	0.675	0.624	0.593	0.570	0.553	0.540	0.528	0.519	0.510	0.503	0.497	0.491	0.481
1	0.2893	0.763	0.690	0.660	0.611	0.581	0.559	0.543	0.530	0.519	0.510	0.502	0.495	0.488	0.483	0.473
2	0.2576	0.744	0.682	0.645	0.598	0.569	0.549	0.533	0.520	0.510	0.501	0.493	0.486	0.480	0.475	0.465
3	0.2294	0.725	0.667	0.631	0.586	0.558	0.539	0.523	0.511	0.501	0.492	0.485	0.478	0.472	0.467	0.458
4	0.2043	0.707	0.652	0.618	0.575	0.548	0.529	0.514	0.502	0.492	0.484	0.477	0.470	0.465	0.460	0.451
5	0.1819	0.690	0.638	0.605	0.564	0.538	0.519	0.505	0.494	0.484	0.476	0.469	0.463	0.458	0.453	0.444
6	0.1620	0.674	0.624	0.592	0.553	0.528	0.510	0.497	0.485	0.476	0.468	0.462	0.456	0.450	0.446	0.437
7	0.1443	0.659	0.611	0.580	0.544	0.519	0.501	0.488	0.477	0.469	0.461	0.455	0.449	0.444	0.439	0.431
8	0.1285	0.645	0.598	0.569	0.533	0.510	0.493	0.480	0.470	0.461	0.454	0.448	0.442	0.437	0.432	0.425

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45. Charging current per single wire, amperes per mile, per 100,000 volts from phase wire to neutral

From formula $I = 2\pi f \times 89.42 \times 10^{-9} \times E[\cosh^{-1}(D/d)]^{-1} = 2\pi f \times 38.83 \times 10^{-9} \times E[\log_{10}(2D/d - d/2D)]^{-1}$

Size cir. mils A. W. G.	Outside diam. in.	Stranded conductor, 25 cycles per sec. Spacing, ft.														
		2	4	5	6	7	8	9	10	11	12	13	14	15	17.5	20
750,000	0.993	0.363	0.307	0.293	0.282	0.274	0.267	0.261	0.256	0.252	0.248	0.244	0.241	0.238	0.232	0.227
600,000	0.889	0.352	0.300	0.286	0.276	0.268	0.261	0.256	0.251	0.247	0.243	0.240	0.237	0.234	0.228	0.223
500,000	0.8111	0.346	0.295	0.282	0.271	0.264	0.256	0.252	0.247	0.243	0.240	0.236	0.233	0.230	0.225	0.220
450,000	0.7695	0.341	0.292	0.279	0.269	0.261	0.254	0.250	0.245	0.241	0.237	0.234	0.231	0.228	0.223	0.218
400,000	0.7255	0.337	0.288	0.275	0.265	0.258	0.251	0.247	0.242	0.239	0.234	0.231	0.229	0.226	0.221	0.216
350,000	0.6786	0.342	0.284	0.271	0.262	0.254	0.248	0.244	0.240	0.235	0.232	0.229	0.227	0.224	0.218	0.214
300,000	0.6211	0.325	0.280	0.268	0.258	0.251	0.245	0.241	0.236	0.232	0.229	0.226	0.224	0.221	0.215	0.211
250,000	0.5669	0.319	0.275	0.263	0.254	0.247	0.242	0.236	0.233	0.229	0.226	0.223	0.221	0.219	0.213	0.208
0000	0.5216	0.312	0.269	0.259	0.250	0.243	0.239	0.233	0.229	0.226	0.223	0.220	0.217	0.215	0.210	0.206
000	0.4645	0.304	0.264	0.253	0.246	0.238	0.234	0.229	0.225	0.222	0.219	0.216	0.214	0.212	0.206	0.202
00	0.4137	0.296	0.259	0.248	0.241	0.234	0.229	0.225	0.221	0.218	0.214	0.213	0.211	0.208	0.203	0.1990
0	0.3683	0.290	0.253	0.243	0.236	0.230	0.225	0.221	0.217	0.214	0.210	0.209	0.207	0.204	0.200	0.1957
1	0.3280	0.282	0.248	0.238	0.232	0.225	0.221	0.216	0.213	0.211	0.207	0.205	0.203	0.201	0.1964	0.1930
2	0.2921	0.275	0.243	0.233	0.227	0.221	0.216	0.212	0.209	0.207	0.204	0.202	0.1995	0.1974	0.1932	0.1896
3	0.2601	0.269	0.237	0.229	0.223	0.217	0.213	0.209	0.206	0.203	0.201	0.1985	0.1965	0.1942	0.1902	0.1868
4	0.2317	0.263	0.233	0.225	0.219	0.213	0.209	0.206	0.203	0.1995	0.1973	0.1953	0.1931	0.1910	0.1872	0.1840

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45. Charging current per single wire, amperes per mile, per 100,000 volts from phase-wire to neutral

Stranded conductor, 60 cycles per sec.

Size cir. mils A. W. G.	Outside diam. in.	Spacing, ft.														
		2	4	5	6	7	8	9	10	11	12	13	14	15	17.5	20.0
750,000	0.993	0.872	0.737	0.703	0.677	0.657	0.641	0.626	0.614	0.604	0.594	0.586	0.579	0.572	0.558	0.545
600,000	0.889	0.845	0.720	0.687	0.663	0.644	0.627	0.614	0.602	0.592	0.583	0.575	0.568	0.562	0.547	0.536
500,000	0.8111	0.830	0.709	0.676	0.653	0.634	0.615	0.605	0.593	0.582	0.574	0.567	0.560	0.553	0.539	0.528
450,000	0.7695	0.819	0.700	0.668	0.644	0.626	0.609	0.599	0.588	0.577	0.569	0.561	0.554	0.548	0.535	0.524
400,000	0.7255	0.808	0.691	0.661	0.636	0.618	0.602	0.593	0.582	0.572	0.562	0.555	0.550	0.543	0.530	0.519
350,000	0.6786	0.796	0.681	0.651	0.628	0.610	0.595	0.585	0.575	0.565	0.556	0.548	0.543	0.537	0.524	0.514
300,000	0.6211	0.780	0.671	0.641	0.619	0.601	0.588	0.577	0.568	0.557	0.549	0.541	0.536	0.530	0.516	0.507
250,000	0.5669	0.765	0.659	0.631	0.610	0.592	0.581	0.568	0.559	0.550	0.542	0.534	0.530	0.524	0.510	0.500
0000	0.5216	0.749	0.646	0.620	0.600	0.583	0.572	0.560	0.549	0.542	0.534	0.527	0.522	0.516	0.504	0.494
000	0.4645	0.730	0.633	0.608	0.590	0.572	0.562	0.550	0.539	0.532	0.524	0.520	0.514	0.508	0.496	0.486
00	0.4137	0.712	0.620	0.595	0.579	0.562	0.550	0.539	0.529	0.523	0.514	0.510	0.506	0.499	0.487	0.478
0	0.3683	0.695	0.608	0.583	0.568	0.551	0.539	0.529	0.521	0.514	0.505	0.501	0.496	0.490	0.479	0.470
1	0.3280	0.676	0.595	0.570	0.556	0.540	0.529	0.519	0.512	0.505	0.497	0.492	0.487	0.482	0.472	0.463
2	0.2921	0.661	0.582	0.560	0.545	0.529	0.519	0.509	0.502	0.496	0.489	0.484	0.480	0.474	0.464	0.456
3	0.2601	0.646	0.570	0.550	0.534	0.520	0.510	0.501	0.494	0.488	0.483	0.476	0.471	0.466	0.457	0.448
4	0.2317	0.631	0.560	0.540	0.524	0.512	0.502	0.494	0.487	0.479	0.474	0.469	0.463	0.458	0.450	0.441

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46. Correcting Factor $\frac{\sinh \theta}{\theta}$

	0.1		0.2		0.3		0.4		0.5	
°		°		°		°		°		°
45	1.00000	0.100	1.00000	0.383	1.00000	0.860	1.00013	1.532	1.00032	2.391
46	0.99993	0.099	0.99975	0.382	0.99950	0.858	0.99920	1.529	0.99888	2.388
47	0.99987	0.098	0.99950	0.381	0.99897	0.856	0.99828	1.526	0.99744	2.385
48	0.99981	0.097	0.99930	0.380	0.99847	0.854	0.99733	1.520	0.99598	2.378
49	0.99975	0.096	0.99910	0.378	0.99797	0.852	0.99640	1.513	0.99454	2.368
50	0.99970	0.094	0.99880	0.376	0.99743	0.848	0.99550	1.506	0.99312	2.357
51	0.99965	0.093	0.99860	0.374	0.99690	0.842	0.99460	1.497	0.99170	2.342
52	0.99960	0.092	0.99840	0.371	0.99640	0.834	0.99370	1.486	0.99028	2.325
53	0.99955	0.091	0.99815	0.367	0.99590	0.826	0.99280	1.472	0.98888	2.304
54	0.99950	0.090	0.99795	0.362	0.99540	0.818	0.99190	1.458	0.98748	2.281
55	0.99944	0.089	0.99775	0.357	0.99490	0.809	0.99103	1.440	0.98610	2.254
56	0.99939	0.088	0.99755	0.352	0.99443	0.799	0.99018	1.421	0.98476	2.226
57	0.99933	0.086	0.99730	0.347	0.99397	0.787	0.98930	1.400	0.98344	2.195
58	0.99928	0.085	0.99705	0.342	0.99347	0.773	0.98845	1.378	0.98212	2.160
59	0.99922	0.083	0.99685	0.336	0.99300	0.760	0.98763	1.354	0.98082	2.123
60	0.99917	0.082	0.99670	0.331	0.99257	0.746	0.98685	1.330	0.97956	2.085
61	0.99912	0.081	0.99645	0.324	0.99213	0.731	0.98603	1.302	0.97832	2.042
62	0.99907	0.079	0.99625	0.317	0.99170	0.715	0.98523	1.273	0.97710	1.998
63	0.99902	0.077	0.99605	0.309	0.99127	0.698	0.98448	1.243	0.97590	1.950
64	0.99897	0.075	0.99585	0.301	0.99083	0.680	0.98373	1.212	0.97476	1.900
65	0.99893	0.073	0.99570	0.293	0.99040	0.661	0.98300	1.179	0.97364	1.848
66	0.99889	0.071	0.99555	0.284	0.99000	0.641	0.98232	1.144	0.97254	1.794
67	0.99885	0.069	0.99540	0.275	0.98963	0.621	0.98165	1.108	0.97150	1.738

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68	0.99881	0.066	0.99520	0.265	0.98927	0.599	0.98100	1.070	0.97046	1.679
69	0.99877	0.064	0.99505	0.255	0.98891	0.577	0.98035	1.030	0.96946	1.617
70	0.99873	0.062	0.99490	0.245	0.98857	0.555	0.97975	0.990	0.96852	1.554
71	0.99869	0.059	0.99475	0.235	0.98823	0.532	0.97918	0.948	0.96760	1.489
72	0.99865	0.057	0.99460	0.225	0.98790	0.508	0.97863	0.905	0.96676	1.422
73	0.99861	0.054	0.99445	0.214	0.98760	0.483	0.97808	0.861	0.96592	1.354
74	0.99858	0.051	0.99435	0.203	0.98733	0.458	0.97758	0.817	0.96514	1.284
75	0.99855	0.048	0.99425	0.192	0.98707	0.432	0.97710	0.771	0.96440	1.212
76	0.99852	0.045	0.99415	0.180	0.98680	0.406	0.97665	0.724	0.96368	1.138
77	0.99850	0.042	0.99405	0.168	0.98653	0.379	0.97625	0.676	0.96304	1.062
78	0.99847	0.039	0.99395	0.156	0.98633	0.351	0.97585	0.628	0.96246	0.986
79	0.99845	0.036	0.99385	0.144	0.98613	0.322	0.97545	0.578	0.96190	0.909
80	0.99843	0.033	0.99375	0.131	0.98593	0.294	0.97512	0.528	0.96134	0.830
81	0.99841	0.030	0.99365	0.118	0.98577	0.266	0.97483	0.477	0.96088	0.750
82	0.99839	0.026	0.99360	0.106	0.98563	0.238	0.97458	0.425	0.96046	0.669
83	0.99838	0.023	0.99355	0.093	0.98553	0.209	0.97433	0.373	0.96008	0.587
84	0.99837	0.020	0.99350	0.080	0.98543	0.180	0.97413	0.321	0.95974	0.505
85	0.99836	0.017	0.99345	0.067	0.98537	0.150	0.97395	0.268	0.95944	0.422
86	0.99835	0.014	0.99340	0.054	0.98530	0.120	0.97380	0.215	0.95920	0.338
87	0.99834	0.011	0.99335	0.041	0.98523	0.090	0.97370	0.162	0.95904	0.254
88	0.99833	0.008	0.99335	0.028	0.98517	0.060	0.97365	0.108	0.95894	0.170
89	0.99832	0.004	0.99335	0.014	0.98510	0.030	0.97360	0.054	0.95890	0.085
90	0.99831	0.000	0.99335	0.000	0.98507	0.000	0.97355	0.000	0.95886	0.000

Example of the use of Table: $\dfrac{\sinh 0.3/80^\circ}{0.3/80^\circ} = 0.98593/0.^\circ294 = 0.98593/0.^\circ17.'38''$

NOTE. $\dfrac{\sinh \theta}{\theta} = 1.0/0^\circ$ when $\theta = 0/\delta$

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46. Correcting Factor $\frac{\sinh \theta}{\theta}$ —*Continued*

	0.6		0.7		0.8		0.9		1.0	
°		°		°		°		°		°
45	1.00070	3.437	1.00134	4.676	1.00230	6.108	1.00363	7.728	1.00553	9.531
46	0.99863	3.437	0.99849	4.679	0.99856	6.112	0.99893	7.735	0.99975	9.546
47	0.99655	3.434	0.99564	4.676	0.99484	6.109	0.99425	7.734	0.99394	9.550
48	0.99445	3.426	0.99281	4.666	0.99114	6.099	0.98955	7.725	0.98816	9.543
49	0.99237	3.414	0.98999	4.652	0.98745	6.082	0.98488	7.707	0.98242	9.525
50	0.99030	3.398	0.98717	4.632	0.98379	6.058	0.98026	7.679	0.97672	9.495
51	0.98825	3.379	0.98439	4.606	0.98015	6.026	0.97567	7.642	0.97105	9.453
52	0.98623	3.355	0.98161	4.574	0.97655	5.987	0.97111	7.595	0.96543	9.399
53	0.98421	3.326	0.97887	4.537	0.97298	5.940	0.96659	7.538	0.95986	9.333
54	0.98220	3.293	0.97616	4.493	0.96944	5.886	0.96211	7.472	0.95435	9.255
55	0.98023	3.256	0.97349	4.445	0.96594	5.824	0.95769	7.396	0.94890	9.166
56	0.97830	3.215	0.97084	4.391	0.96249	5.755	0.95333	7.312	0.94353	9.065
57	0.97638	3.171	0.96823	4.331	0.95909	5.678	0.94904	7.218	0.93825	8.952
58	0.97448	3.122	0.96564	4.265	0.95574	5.593	0.94482	7.114	0.93305	8.827
59	0.97262	3.069	0.96313	4.193	0.95244	5.502	0.94067	7.000	0.92795	8.691
60	0.97081	3.013	0.96067	4.117	0.94923	5.405	0.93661	6.878	0.92295	8.544
61	0.96903	2.953	0.95826	4.036	0.94608	5.300	0.93263	6.747	0.91805	8.385
62	0.96728	2.889	0.95589	3.951	0.94299	5.189	0.92874	6.607	0.91325	8.215
63	0.96557	2.821	0.95356	3.859	0.93996	5.070	0.92493	6.458	0.90856	8.033
64	0.96390	2.749	0.95130	3.762	0.93703	4.944	0.92121	6.300	0.90400	7.841
65	0.96228	2.674	0.94911	3.661	0.93416	4.812	0.91761	6.136	0.89957	7.637
66	0.96072	2.596	0.94697	3.554	0.93140	4.674	0.91411	5.962	0.89527	7.424
67	0.95922	2.515	0.94493	3.444	0.92873	4.529	0.91074	5.780	0.89111	7.201

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68	0.95775	2.430	0.94293	3.329	0.92614	4.379	0.90747	5.590	0.88708	6.908
69	0.95632	2.342	0.94100	3.209	0.92364	4.223	0.90430	5.392	0.88320	6.723
70	0.95495	2.251	0.93914	3.085	0.92123	4.061	0.90127	5.187	0.87947	6.460
71	0.95365	2.157	0.93737	2.957	0.91891	3.894	0.89837	4.975	0.87590	6.207
72	0.95242	2.061	0.93569	2.825	0.91671	3.722	0.89558	4.456	0.87247	5.936
73	0.95123	1.962	0.93407	2.690	0.91461	3.544	0.89292	4.330	0.86921	5.656
74	0.95010	1.860	0.93254	2.550	0.91261	3.361	0.89041	4.298	0.86612	5.368
75	0.94902	1.756	0.93109	2.408	0.91073	3.174	0.88804	4.059	0.86320	5.073
76	0.94802	1.649	0.92973	2.263	0.90895	2.982	0.88581	3.815	0.86045	4.766
77	0.94707	1.540	0.92846	2.114	0.90729	2.787	0.88372	3.566	0.85788	4.458
78	0.94620	1.429	0.92727	1.962	0.90574	2.588	0.88177	3.312	0.85549	4.141
79	0.94540	1.317	0.92617	1.808	0.90431	2.385	0.87997	3.053	0.85328	3.818
80	0.94465	1.203	0.92516	1.652	0.90301	2.179	0.87831	2.789	0.85125	3.489
81	0.94397	1.087	0.92424	1.493	0.90183	1.969	0.87681	2.522	0.84940	3.156
82	0.94337	0.970	0.92343	1.332	0.90076	1.757	0.87547	2.251	0.84774	2.817
83	0.94283	0.852	0.92270	1.169	0.89981	1.543	0.87428	1.976	0.84628	2.474
84	0.94237	0.732	0.92207	1.005	0.89899	1.327	0.87324	1.699	0.84501	2.128
85	0.94197	0.612	0.92153	0.839	0.89829	1.109	0.87237	1.420	0.84393	1.779
86	0.94163	0.490	0.92109	0.673	0.89771	0.889	0.87164	1.138	0.84305	1.426
87	0.94138	0.368	0.92074	0.506	0.89726	0.668	0.87108	0.855	0.84236	1.071
88	0.94122	0.246	0.92050	0.338	0.89694	0.446	0.87068	0.571	0.84186	0.715
89	0.94110	0.123	0.92036	0.169	0.89675	0.223	0.87043	0.286	0.84156	0.358
90	0.94107	0.000	0.92031	0.000	0.89670	0.000	0.87037	0.000	0.84147	0.000

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47. Correcting Factor $\frac{\tanh \theta}{\theta}$

Note.—All the angles found in this table are negative

	0.1		0.2		0.3		0.4		0.5	
°		°—		°—		°—		°—		°—
45	1.00000	0.188	0.99985	0.765	0.99937	1.718	0.99803	3.046	0.99514	4.750
46	1.00010	0.188	1.00030	0.764	1.00040	1.719	0.99988	3.055	0.99804	4.771
47	1.00021	0.188	1.00075	0.763	1.00143	1.720	1.00173	3.058	1.00094	4.781
48	1.00033	0.188	1.00120	0.761	1.00250	1.717	1.00358	3.058	1.00384	4.787
49	1.00044	0.187	1.00170	0.758	1.00357	1.710	1.00543	3.053	1.00680	4.787
50	1.00056	0.187	1.00215	0.755	1.00460	1.703	1.00733	3.045	1.00980	4.780
51	1.00068	0.187	1.00265	0.749	1.00563	1.694	1.00925	3.031	1.01278	4.767
52	1.00080	0.186	1.00310	0.744	1.00670	1.685	1.01115	3.014	1.01578	4.747
53	1.00092	0.184	1.00355	0.738	1.00773	1.672	1.01303	2.995	1.01878	4.724
54	1.00103	0.182	1.00405	0.732	1.00877	1.656	1.01490	2.969	1.02178	4.692
55	1.00114	0.180	1.00450	0.724	1.00980	1.638	1.01675	2.942	1.02478	4.656
56	1.00125	0.177	1.00495	0.715	1.01083	1.618	1.01865	2.911	1.02778	4.612
57	1.00135	0.175	1.00535	0.705	1.01183	1.596	1.02050	2.876	1.03076	4.561
58	1.00146	0.172	1.00575	0.694	1.01283	1.574	1.02330	2.836	1.03374	4.506
59	1.00156	0.170	1.00620	0.682	1.01380	1.548	1.02410	2.793	1.03670	4.444
60	1.0017	0.167	1.0067	0.668	1.0148	1.521	1.0259	2.745	1.0397	4.375
61	1.0018	0.163	1.0070	0.655	1.0158	1.490	1.0278	2.695	1.0425	4.300
62	1.0019	0.159	1.0074	0.640	1.0167	1.458	1.0294	2.641	1.0454	4.220
63	1.0020	0.155	1.0078	0.625	1.0176	1.425	1.0311	2.583	1.0482	4.133
64	1.0020	0.151	1.0082	0.609	1.0185	1.390	1.0328	2.521	1.0510	4.041
65	1.0021	0.147	1.0086	0.592	1.0193	1.353	1.0344	2.456	1.0538	3.942
66	1.0022	0.143	1.0090	0.575	1.0202	1.314	1.0360	2.388	1.0564	3.836
67	1.0023	0.138	1.0093	0.557	1.0210	1.273	1.0376	2.315	1.0591	3.724

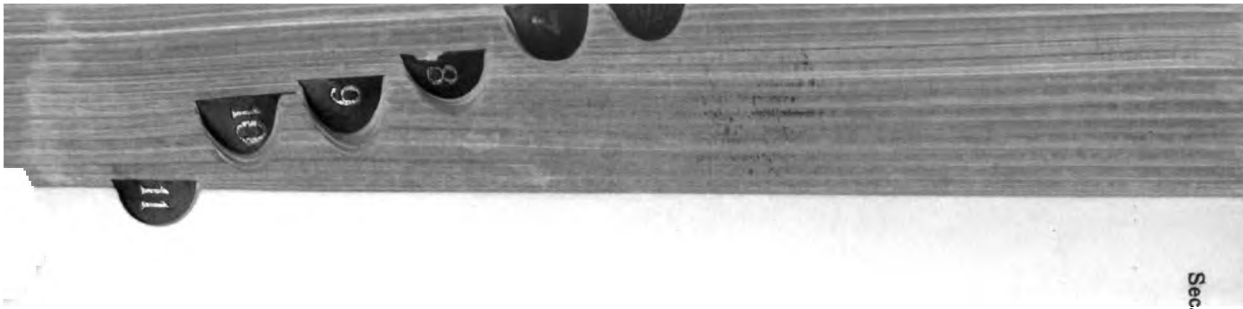
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68	1.0024	0.134	1.0097	0.539	1.0218	1.231	1.0391	2.240	1.0617	3.609
69	1.0025	0.129	1.0100	0.520	1.0226	1.187	1.0406	2.163	1.0642	3.489
70	1.0026	0.123	1.0103	0.499	1.0234	1.141	1.0420	2.082	1.0666	3.362
71	1.0026	0.118	1.0106	0.478	1.0241	1.094	1.0434	1.998	1.0689	3.229
72	1.0027	0.112	1.0109	0.456	1.0247	1.045	1.0447	1.911	1.0712	3.091
73	1.0028	0.107	1.0112	0.434	1.0254	0.995	1.0460	1.821	1.0734	2.948
74	1.0028	0.102	1.0114	0.411	1.0260	0.944	1.0472	1.728	1.0755	2.800
75	1.0029	0.096	1.0117	0.388	1.0266	0.892	1.0483	1.632	1.0774	2.649
76	1.0029	0.090	1.0120	0.365	1.0272	0.838	1.0494	1.534	1.0793	2.493
77	1.0030	0.084	1.0122	0.341	1.0277	0.783	1.0504	1.434	1.0811	2.333
78	1.0030	0.078	1.0123	0.316	1.0282	0.727	1.0513	1.332	1.0828	2.169
79	1.0031	0.072	1.0125	0.291	1.0287	0.671	1.0522	1.229	1.0843	2.001
80	1.0031	0.066	1.0127	0.266	1.0291	0.614	1.0530	1.124	1.0857	1.830
81	1.0032	0.060	1.0129	0.241	1.0295	0.555	1.0538	1.017	1.0870	1.656
82	1.0032	0.054	1.0130	0.215	1.0298	0.494	1.0544	0.908	1.0881	1.480
83	1.0032	0.047	1.0132	0.188	1.0301	0.433	1.0550	0.797	1.0892	1.301
84	1.0033	0.040	1.0133	0.162	1.0304	0.372	1.0555	0.685	1.0901	1.119
85	1.0033	0.033	1.0134	0.136	1.0307	0.311	1.0560	0.573	1.0908	0.935
86	1.0033	0.026	1.0134	0.109	1.0309	0.249	1.0563	0.460	1.0914	0.749
87	1.0033	0.019	1.0135	0.082	1.0310	0.187	1.0566	0.346	1.0919	0.562
88	1.0033	0.012	1.0135	0.054	1.0311	0.125	1.0568	0.232	1.0923	0.374
89	1.0033	0.006	1.0135	0.027	1.0311	0.063	1.0570	0.117	1.0926	0.187
90	1.0033	0.000	1.0136	0.000	1.0311	0.000	1.0570	0.000	1.0926	0.000

Example of the use of Table: $\frac{\tanh 0.4\angle 71°}{0.4\angle 71°} = 1.0434\angle 1.°998 = 1.0434\angle 1.°59.'53''.$

NOTE. $\frac{\tanh \theta}{\theta} = 1.0\angle 0°$ when $\theta = 0\angle \delta$.

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47. Correcting Factor $\frac{\tanh \theta}{\theta}$ —*Continued*

	0.6		0.7		0.8		0.9		1.0	
°		°_		°_		°_		°_		°_
45	0.99010	6.817	0.98189	9.214	0.96971	11.902	0.95284	14.839	0.93077	17.956
46	0.99417	6.854	0.98727	9.281	0.97646	12.020	0.96089	15.020	0.93999	18.216
47	0.99830	6.881	0.99279	9.337	0.98339	12.122	0.96921	15.185	0.94950	18.461
48	1.00248	6.901	0.99840	9.383	0.99050	12.210	0.97779	15.334	0.95938	18.692
49	1.00672	6.912	1.00410	9.419	0.99780	12.285	0.98665	15.469	0.96966	18.908
50	1.01100	6.915	1.00991	9.443	1.00526	12.347	0.99578	15.588	0.98032	19.108
51	1.01533	6.908	1.01581	9.455	1.01289	12.395	1.00518	15.690	0.99136	19.290
52	1.01970	6.893	1.02181	9.457	1.02069	12.427	1.01486	15.777	1.00282	19.455
53	1.02412	6.870	1.02789	9.445	1.02864	12.444	1.02479	15.845	1.01469	19.600
54	1.02855	6.838	1.03403	9.423	1.03675	12.446	1.03500	15.895	1.02697	19.726
55	1.03300	6.797	1.04024	9.388	1.04501	12.432	1.04549	15.925	1.03970	19.828
56	1.03747	6.746	1.04653	9.338	1.05343	12.401	1.05626	15.934	1.05287	19.909
57	1.04195	6.685	1.05286	9.375	1.06196	12.453	1.06729	15.922	1.06648	19.965
58	1.04642	6.616	1.05921	9.200	1.07061	12.288	1.07854	15.889	1.08054	19.996
59	1.05089	6.537	1.06561	9.112	1.07939	12.203	1.09007	15.833	1.09506	19.998
60	1.05537	6.448	1.07210	9.010	1.08829	12.100	1.10188	15.753	1.11009	19.973
61	1.05980	6.350	1.07856	8.893	1.09726	11.978	1.11390	15.647	1.12555	19.918
62	1.06420	6.242	1.08500	8.762	1.10630	11.835	1.12614	15.514	1.14144	19.832
63	1.06858	6.124	1.09143	8.617	1.11540	11.673	1.13856	15.355	1.15777	19.711
64	1.07293	5.998	1.09783	8.458	1.12456	11.491	1.15116	15.169	1.17454	19.555
65	1.07722	5.862	1.10420	8.285	1.13373	11.288	1.16392	14.956	1.19173	19.362
66	1.08143	5.716	1.11053	8.098	1.14291	11.064	1.17684	14.711	1.20935	19.131
67	1.08560	5.561	1.11683	7.895	1.15208	10.820	1.18989	14.438	1.22737	18.860

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68	1.08967	5.397	1.12299	7.678	1.16118	10.552	1.20298	14.132	1.24569	18.545
69	1.09363	5.223	1.12904	7.447	1.17020	10.263	1.21608	13.796	1.26429	18.188
70	1.09750	5.041	1.13500	7.202	1.17915	9.953	1.22919	13.428	1.28316	17.785
71	1.10125	4.850	1.14083	6.943	1.18796	9.621	1.24226	13.026	1.30221	17.334
72	1.10490	4.650	1.14651	6.671	1.19659	9.268	1.25524	12.592	1.32140	16.836
73	1.10842	4.441	1.15201	6.386	1.20503	8.894	1.26807	12.126	1.34063	16.290
74	1.11180	4.225	1.15734	6.087	1.21325	8.499	1.28067	11.628	1.35986	15.693
75	1.11503	4.002	1.16244	5.775	1.22121	8.083	1.29300	11.097	1.37894	15.043
76	1.11810	3.772	1.16733	5.450	1.22889	7.648	1.30500	10.532	1.39775	14.342
77	1.12102	3.534	1.17197	5.114	1.23623	7.192	1.31659	9.936	1.41620	13.591
78	1.12375	3.289	1.17636	4.767	1.24319	6.718	1.32772	9.309	1.43412	12.788
79	1.12628	3.038	1.18046	4.409	1.24976	6.227	1.33830	8.653	1.45141	11.935
80	1.12863	2.781	1.18427	4.042	1.25591	5.718	1.34827	7.966	1.46790	11.032
81	1.13078	2.519	1.18777	3.666	1.26158	5.195	1.35754	7.254	1.48345	10.081
82	1.13273	2.251	1.19094	3.281	1.26674	4.656	1.36607	6.517	1.49790	9.087
83	1.13447	1.979	1.19377	2.888	1.27138	4.104	1.37378	5.757	1.51110	8.052
84	1.13598	1.704	1.19626	2.488	1.27545	3.540	1.38059	4.975	1.52289	6.977
85	1.13727	1.425	1.19839	2.083	1.27895	2.966	1.38646	4.175	1.53314	5.868
86	1.13832	1.144	1.20013	1.672	1.28185	2.383	1.39132	3.360	1.54170	4.731
87	1.13915	0.860	1.20150	1.257	1.28413	1.794	1.39518	2.532	1.54848	3.571
88	1.13975	0.574	1.20247	0.839	1.28575	1.199	1.39793	1.692	1.55339	2.391
89	1.14010	0.287	1.20306	0.420	1.28671	0.600	1.39959	0.847	1.55637	1.198
90	1.14022	0.000	1.20327	0.000	1.28700	0.000	1.40017	0.000	1.55740	0.000

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SYSTEM DISTURBANCES

48. Surges* and disturbances occur in a transmission circuit, when circuit conditions are in any way altered. An **oscillation** is a recurring disturbance due usually to the oscillation of energy between the electrostatic and electromagnetic fields. An oscillation of low frequency, or one that is rapidly damped, is called a **surge.** Disturbances may be produced by causes within the system itself, such as switching, grounds, changes of load, or they may be produced by external causes, such as lightning.

In an oscillation, the energy passes from one form to the other, so that, assuming no loss,

$$\tfrac{1}{2}Li^2 = \tfrac{1}{2}Ce^2$$

or

$$e/i = \sqrt{L/C} \tag{23}$$

e is the voltage produced by a sudden suppression of the current i. L and C are the line inductance and capacitance respectively. If the line resistance and leakance are negligible, the term $\sqrt{L/C}$ is usually called the *natural or surge impedance* of the line.

From Eq. 23, the maximum voltage possible to occur on suppression of the current I is:

$$e = I\sqrt{L/C} \tag{24}$$

This rise of voltage limits the current that may safely be interrupted and renders a short-circuit dangerous.

Any change in load will alter either e or i and as the energy of the electrostatic and electromagnetic fields cannot change in zero time, e and i must pass through some transient values before the steady state is again reached.

If r, the resistance, is equal to or greater than $\sqrt{L/C}$, the transient is non-oscillatory, and quickly dies out. If r is less than $\sqrt{L/C}$, the transient is oscillatory. The energy is dissipated as heat in the resistance, in hysteresis losses in the fields themselves, or the insulation of the system may break down allowing the energy to manifest itself in an arc.

In the above relations the constants of the line loads and of the terminal apparatus have been neglected.

49. The frequency at which the transient oscillates is

$$f = 1/(4\sqrt{LC}) \tag{25}$$

when the line is open at one end and grounded at the other. If the line is open at both ends, $f = 1/2\sqrt{LC}$. f is the *natural frequency* of the circuit. The transmission frequency should be so chosen that the natural frequency is not exactly an odd multiple thereof.

50. A wave of potential or current attenuates in magnitude and phase as it travels along a transmission line. The **propagation constant** per unit length of line is a and the **propagation factor** is $\epsilon^{-a} = \epsilon^{-a_1} \times \epsilon^{-ja_2}$, where ϵ is the Naperian logarithmic base, and $a = a_1 + ja_2 = \sqrt{zy} = \sqrt{(r + jl\omega)\ (g + jc\omega)}$; z, r, and l are respectively the impedance, resistance and inductance per unit length of line; y, g, and c are respectively the admittance, leakage conductance and capacitance per unit length of line; $\omega = 2\pi f$, where f is the frequency; r and z are expressed in ohms, y and g in mhos, l in henrys, and c in farads all per unit length of line. a_1 is the **attenuation constant** and a_2 is the **retardation angle** per unit length of line. If the line is long or if its terminal load impedance is equal to the line surge impedance. ϵ^{-a_1} gives the shrinkage in amplitude of the current or voltage per unit length of line; ϵ^{-ja_2} has the properties of a circular angle a_2 radians and is the factor which shows the lag (space phase) of the wave occurring in each unit length of the line. After a wave has traversed l' units length of the line, its phase lags behind the wave then being delivered by the generator $l'a_2$ radians. $a = a_1 + j\varphi_2$ may also be called the hyperbolic angle per unit length of line. As an example, if $a = 0.000072 + j\ 0.0007854$ hyperbolic radians per mile, an initial voltage wave of 100 volts traveling along the

* Bibliography 27-30.

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line becomes 93.05 volts at the end of the first 1000 miles and lags 0.7854 circular radians or 45 deg. behind the wave then being delivered by the generator. Roughly, in each unit length of line, a wave shrinks in amplitude by an amount equal to α_1 times its initial amplitude.

Over the entire line of length l, an initial voltage wave E attenuates to a voltage E_2 where $E_2 = Ee^{-\theta} = Ee^{-\theta_1 - j\theta_2} = E(e^{-\theta_1} \times e^{-j\theta_2})$; $\theta = l'\alpha$; $\theta_1 = l'\alpha_1$; $\theta_2 = l'\alpha_2$; θ is the propagation constant of the entire line. θ_1 is the attenuation constant and θ_2 is the retardation angle for the entire line $e^{-\theta_1}$ is the amount a current or voltage wave traveling along the entire line shrinks in amplitude, and such a wave lags θ_2 radians behind the wave then being delivered by the generator, a single wave only being considered.

A wave of frequency f travels over the line with an apparent or group velocity $v = \frac{\omega}{\alpha_2}$, where $\omega = 2\pi f$. If α_2 is given for one kilometer of line, v = kilometers per second.

If $r = 0$, and $g = 0$, $v = 1/\sqrt{lc}$. For a free, uniform line surrounded by air, in which the internal inductance is neglected, v is 300,000 kilometers per second very nearly, the velocity of light. The actual velocity of propagation ω/α_2 is less than this, due to the presence of resistance, leakance, etc., which dissipate energy.

The **wave length** $\lambda = 2\pi/\alpha_2$, holds for the steady state and for the transient state as well. λ is the distance a wave must travel to lose one cycle or 2π radians with respect to the generator phase.

The complex quantity $\sqrt{(r + jl\omega)/(g + jc\omega)} = \sqrt{z/y} = z_0$ is usually called the **surge impedance**, the **natural impedance** or the **characteristic impedance** of the line. z_0 is the impedance that the line offers at any point to an advancing wave of the frequency under consideration. That is, the current $i = e/z_0$, where i is an advancing current wave, and e the corresponding voltage wave. If the resistance and leakance be neglected, $z_0 = \sqrt{l/c}$.

The surge or natural impedance of the entire line is $Z_0 = \sqrt{Z/Y}$. If the resistance and leakance be neglected, $Z_0 = \sqrt{L/C} = \sqrt{l/c}$.

The propagation constant $\sqrt{ZY}$ and the surge impedance $\sqrt{Z/Y}$ both appear in equations 19 and 20, Par. 31.

51. Forced oscillations are produced by a source of energy external to the circuit, such as lightning, whose frequency has no relation to the circuit constants. The frequency of such oscillations is that of the source of energy. The disturbances which often *follow* such forced oscillations have frequencies that *are determined by the line constants* and the terminal impedances.

52. Effect of transients. When a traveling wave passes from one part of a circuit into another of different constants, the voltage wave, e_1, will change its magnitude to e_2, as follows,

$$e_2 = e_1 \frac{Z_2}{\left(\frac{Z_1 + Z_2}{2}\right)} \qquad (26)$$

and the current

$$i_2 = i_1 \frac{Z_1}{\left(\frac{Z_1 + Z_2}{2}\right)} \qquad (27)$$

where Z_1 and Z_2 are the surge or natural impedances which are equal, neglecting losses, to $\sqrt{L_1/C_1}$ and $\sqrt{L_2/C_2}$ of the two parts of the circuit, respectively. (See Pars. 48 and 50.) Thus a wave passing from one part of a circuit to another having a greater ratio of inductance to capacitance will develop an increased voltage and a decreased current. This explains the breaking down of transformer windings, due to surges entering them. On the other hand, if a wave passes from an overhead system into a cable, the voltage will be reduced, and the current increased. This explains the self-protecting quality of cables to surges.

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53. A line whose length is a quarter wave is determined as a first approximation by

$$L = \frac{186{,}000}{4f} \tag{28}$$

where L is the length in miles, f the frequency in cycles per sec., and 186,000 the velocity of light in miles per second and also the velocity of an electric wave in miles per sec. if all losses be neglected. Actually the wave velocity is much less than this value owing to the presence of resistance, leakance, etc. It can be shown that such a line, with constant generator voltage, tends to regulate for constant current at the receiving end, and the maintenance of constant voltage at the load therefore becomes difficult. The voltage may rise to dangerous values when the circuit is open, though a load at the receiving end tends to neutralize this abnormal potential. The frequency corresponding to a quarter wave length of line is the lowest frequency at which the line can freely oscillate. It cannot oscillate at a frequency corresponding to either a half or a whole wave length when the circuit is open at one end.

54. Oscillations originating in the transformer. High voltage transformers have an appreciable electrostatic capacitance between turns, and also to ground, together with a large equivalent reactance. This not only tends to create very high frequency oscillations in the transformer itself, but also to produce voltage rises that may puncture the insulation. Protective apparatus must therefore be so designed that these oscillations may be suppressed within the transformer or readily pass from the transformer to the line, while, at the same time, outside disturbances will be prevented from passing in the reverse direction.

55. Lightning disturbances* may be due to a charge induced on the line by a nearby cloud which discharges, thus allowing the line charge to flow suddenly to ground; to inductive action of a nearby discharge; to direct stroke. Such disturbances may be of high frequency and may either start a destructive arc to ground or shatter the insulators near the spot of original disturbance. Waves may be propagated in both directions, causing damage at some remote point.

56. Lightning disturbances may be minimized by the use of one or more overhead ground wires, grounded at frequent intervals. Damage to apparatus may be practically prevented by installing arresters, preferably of the aluminum cell type, near the apparatus, for example, across the high-tension bus bars at the generating station; at substation entries; and near outdoor transformers and substations. Lines have been protected by operating them just below the critical corona voltage (see Par. **65** to **69**). Any disturbance that tends to raise the voltage, immediately increases the corona loss to such an extent that the energy of the disturbance is thereby dissipated.

57. The selection of protective equipment is governed somewhat by local conditions. The degree of protection necessary depends largely upon the value of the power that is being transmitted, and the financial loss involved by a shut-down or by an interruption of the service.

58. Local short-circuits may be isolated from the rest of the system by properly selected automatic oil switches equipped with relays which are of either the instantaneous, reverse-energy, or inverse-time-limit types. Lightning arresters should be able to care for any abnormal voltage rise due to switching. (See Pars. **48** and **97**.) To prevent the current flowing into a short circuit in one portion of the system rising to dangerous values, power-limiting reactances are interposed between the different sections of the system.

59. Detection and clearing of grounds. Grounds may be detected by some form of electrostatic detector, placed on the switchboard. An arcing-ground on an ungrounded system may be cleared by the **arcing ground suppressor**, shown in Fig. 25. The selective relay may operate electrostatically, or electromagnetically by the use of potential transformers.

*Creighton, E. E. F. "Protection of Electrical Transmission Lines." *Trans.* A. I. E. E., Vol. XXX (1911), p. 257.

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When a **ground occurs** on any phase, that phase is temporarily grounded by the proper oil switch, selectively operated by the relay. This lowers the voltage across the arc, which therefore ceases, and the switch then opens (through a resistance to prevent oscillations) and the ground is thus cleared. In a cable system the grounded phase is permanently connected to ground, as otherwise the arc would immediately re-form when the switch opened, due to the short distance between core and sheath. Interlocking devices prevent the simultaneous operation of more than one switch at a time, thus avoiding a short-circuit on the system.

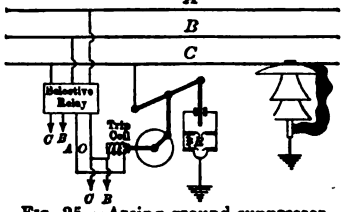


FIG. 25.—Arcing-ground suppressor.

A **short-circuit suppressor** throws a fuse directly between phases, shunting out a short-circuit arc. Subsequently the fuse automatically interrupts its own current. When these are used, power-limiting reactances are desirable in order to protect apparatus from mechanical injury.

60. Overhead ground wires unquestionably reduce the interruptions to service due to lightning, although there are no available data stating just how great the advantage is. It is estimated that one wire will reduce these interruptions about 50 per cent., and that two wires will make a still greater reduction. Galvanised iron and steel, because of their low cost and high tensile strength, have been commonly used for this purpose. Copper-clad conductors may have a lower impedance to the high-frequency discharges of lightning than either galvanised iron or steel.

GENERAL FEATURES OF DESIGN

61. The conductor for a given transmission system is influenced by such factors as climate, topography, length of span, reliability, amount of power, transmission distance and the economics of the problem. Copper, aluminum and aluminum steel re-inforced (aluminum cable with a steel core) (see Sec. 4), except in special cases, are used extensively for the conductors. Copper has high conductivity, is very ductile, is not easily abraded, has high tensile strength, a high melting point, and can be readily soldered. Aluminum has a conductivity about 60 per cent. that of copper. For the same conductance, it has only one-half the weight of copper. It is ductile and easily abraded; has 1.4 times the linear coefficient of expansion of copper, giving greater sag, and would therefore require higher towers for the same length of span. The tensile strength of all aluminum cable is much less than that of copper, though the ratio of tensile strength to weight is greater for aluminum. The tensile strength of aluminum steel-reinforced cable compares favorably with that of copper. (See Par. **109.**) The melting point of aluminum is lower than that of copper, so that aluminum will be more easily burned by arcs and short-circuits. For the same conductance, aluminum offers a greater surface to wind-pressure, so towers must be designed with greater transverse strength. All-aluminum cable is not recommended for sizes smaller than 4/0. Neither copper nor aluminum is attacked by the atmosphere to any extent. In the United States, the price of aluminum is always held slightly below that of copper of the same conductance. In view of increased cost of pole line necessary to its employment, there is comparatively little incentive to use aluminum in small sizes of wire. In Canada and on the Continent of Europe, aluminum has found favor.

62. For extra long spans, it may be found economical to use either iron or steel as conductors, because of their much greater tensile strength. As these metals are subject to corrosion, they must either be galvanised or "copper-clad." Phosphor-bronze has been proposed, but its much higher cost for the same conductance practically prohibits its use. The table in Par. **63** shows a comparison of various conductor materials, and more complete tables may be found in Sec. 4.

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63. Comparison of conductor materials on basis of equal conductance

Metal	Diameter	Weight	Strength	*Cost relation
Copper	1.00	1.00	1.00	1.00
Aluminum	1.27	0.485	0.65	2.06
Alum. steel re-inforced.	1.36	0.66–0.90	1.0 (smaller sizes) to 2.0 (larger)	1.2–1.5
Iron	2.72	6.36	5.30	0.157
Steel	3.41	10.00	41.5	0.100
Copper-clad steel	1.52	2.12	4.4	0.47

NOTE.—Skin effect has been neglected. Skin effect tables are given in Sec. 4. The relative resistivities have been taken as follows: copper = 1; aluminum = 1.61; iron = 7.4; steel = 11.6; copper-clad steel = 2.3. The specific gravities are: copper = 8.89; aluminum = 2.68; iron and steel = 7.64; and copper-clad steel = 8.20. The elastic limits are: copper = 35,000 lb. per sq. in.; aluminum (stranded) = 14,000 lb. per sq. in.; iron = 25,000 lb. per sq. in.; steel = 125,000 lb. per sq. in.; and copper-clad steel = 68,000 lb. per sq. in.

64. Required size of conductor is determined by (a) mechanical strength; (b) permissible energy loss; (c) required voltage regulation; (d) corona; (e) cost; (f) current-carrying capacity.

(a) **Mechanical strength** is a primary consideration in any transmission line. It becomes especially important where long spans are necessary.

(b) **Permissible energy loss** is determined by such factors as the cost of generating power, selling price, load-factor, and other economic considerations. Where power is produced cheaply, it may be more economical to lose power in the line than to pay the fixed charges incident to heavier conductors and poles. (See Economics.)

(c) **Required voltage regulation** is, in general, not difficult to secure, as automatic regulators and synchronous apparatus may take care of any voltage fluctuations at the sub-stations. If, however, the inductive line drop for a given cross-section of conductor is too great, two separate lines of half the cross-section may be used. The additional cost of insulators, poles and construction seldom justifies duplicate lines, where better regulation alone is the requirement.

(d) **Corona** may make the energy loss in excess of the permissible value, in which case it will be necessary to increase the conductor diameter or the effective size of conductor. See Par. **65** to **69** incl.

(e) **Cost,** such as the relative cost of line, of plant, and of line maintenance may determine the size of line conductors. Since the salvage value of the line is in general low, whereas the engines and dynamos of the central station may be transferred without excessive loss to another plant and again used, it is advantageous to put more money into the generating station and to build the line as cheaply as possible if the system is a temporary affair. The amount of money available may make it necessary to build the system at a minimum cost, in which case the line conductors must be so chosen that the cost of the line plus the cost of the station, to supply both the net load and the line loss, shall be a minimum. The larger the line conductors, the smaller will be the energy loss, but the fixed charges for the line will be increased. The conductors may be so chosen that the sum of these last two quantities is a minimum. See Par. **236.**

(f) **Current-carrying capacity** of the conductors, under continuous operating conditions, is usually ample when the size of wire is determined by the permissible energy loss. An emergency demand, however, may overload the line for a short time, and where this is likely to occur, the conductor should be of such size as to operate within safe temperature limits. Tables of safe carrying capacity are given in Sec. 12.

* The last column in the table shows what *should* be the relation in cost per lb. of the various materials to result in the same total cost of conductor where the conductance of the line is fixed.

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CORONA

65. Electric Corona occurs when the potential of a conductor in air is raised to such a value that the dielectric strength of the surrounding air is exceeded. Corona manifests itself by bluish tufts or streamers appearing around the conductor, being more or less concentrated at irregularities on the conductor surface. This discharge is accompanied by a hissing sound, and by the odor of ozone. In the presence of moisture, nitrous acid is produced. Corona is due to ionization of the air. The ions are repelled from the conductor at high velocity, producing other ions by collision. The ionized air is a conductor of high resistance and increases the effective diameter of the original conductor.

If the distance between two insulated cylindrical conductors is small as compared with their diameters, it may not be possible for corona to form, for as soon as the dielectric strength of the air is exceeded, it breaks down, throwing more stress on the remaining layers of air, which in turn break down, and spark-over results. If, however, a sufficient distance exists between the conductors (about 15 times the conductor diameter), the undisrupted air may be able to support the dielectric stress existing between the conductors, even although the disrupted air in the neighborhood of the conductors has decreased the effective length of the dielectric path between the conductors.

Corona represents an energy loss, which on a long transmission line may be substantial. H. J. Ryan, R. D. Mershon, J. B. Whitehead, and F. W. Peek have made important investigations of corona. Peek's tests were made on a line consisting of two transmission spans and having a total length of about 900 ft., using various conductors, spacings, and at different temperatures, etc. His conclusions are as follows:

The *disruptive gradient* of the air, g_o, is constant for all conductors and frequencies at 25 deg. C. and 76 cm. barometer, being 21.1 kv. per cm. effective or 29.8 kv. per cm. maximum, and is given by $g_o = \dfrac{e_o}{r \log_e \dfrac{S}{r}}$, where

e_o is the *disruptive critical voltage* in kilovolts to *neutral*, r the conductor radius in *cm.*, and S the distance between conductor centers in cm. If 21.1 kv. per cm. is used for g_o, e_o is given in *effective* volts.

$$e_o = g_o M_o r \delta \log_e \frac{S}{r} \qquad (29)$$

e_o is affected by the air density-factor δ and also by the condition of the conductor surface, which is taken into account by the conductor irregularity factor M_o. $M_o = 1$ for polished wires; 0.98 to 0.93 for roughened or weathered wires; 0.87 to 0.83 for 7-strand cable. $\delta = 3.92b/(273+t)$; b = barometric pressure in cm.; t = temp. in deg. cent.; $\delta = 1$ at 76 cm. pressure and 25 deg. cent.; $\log_e = 2.303 \log_{10}$; values of δ for various altitudes are given in Par. **67**. The tables in Par. 66 give values of e_o.

E_v, the voltage at which corona becomes *visible*, is given by:

$$E_v = M_v g_o \delta r \left(1 + \frac{0.301}{\sqrt{\delta r}}\right) \log_e \frac{S}{r} \text{ kv. to neutral.} \qquad (30)$$

$M_v = M_o = 1$ for polished conductors. When $M_v = 0.72$, local corona exists all along the conductor, and when $M_v = 0.62$ there is decided corona all along the conductor for 7-strand cables.

E_v is always greater than e_o. Theoretically no corona loss exists until E_v is reached, but actually corona loss begins at the lesser value of voltage e_v due to dirt, irregularities, etc., on the conductor surface. With a truly cylindrical, highly-polished conductor, no loss would occur probably, below the voltage E_v. The reason that corona does not become *visible* at the voltage e_o is due to the fact that the gradient at a finite distance from the conductor must exceed g_o in order to give the ions opportunity to attain velocity, and thus produce other ions by collision.

The power loss P in kilowatts per kilometer per conductor is given by

$$P = \frac{k}{\delta} f \sqrt{\frac{r}{S}} (e - e_o)^2 10^{-5}. \qquad (31)$$

where $k = 344$; f is the frequency in cycles per second; e the kilovolts to neutral

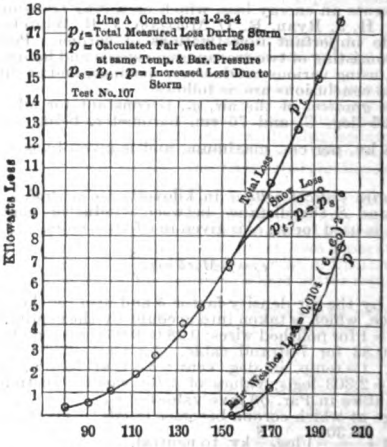
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effective (corresponding to $g_o = 21.1$ kv. per cm.). In English units the power loss becomes:

$$P = \frac{552}{\delta} f \sqrt{\frac{r}{S}} \left[e - 123.4 M_o r \delta \log_{10} \frac{S}{r}\right]^2 10^{-5} \text{ kw. per wire mile.} \quad (32)$$

where e = effective volts to neutral; $\delta = \dfrac{17.91 b}{459 + t}$; $\delta = 1$ at 77 deg. fahr. and 29.92 in. barometer; b = barometric pressure in inches; r = *radius* of conductor in inches; S = distance between conductor centers in inches; f = frequency in cycles per second; M_o = irregularity factor; $M_o = 1$ for polished wires, etc.

The above equations show that corona loss is proportional to the frequency. This holds true for the range of frequencies used in the tests, 47 to 120 cycles per second. The law departs from the linear relation at low frequencies. At zero frequency, (that is direct current), the loss is from ¼ to ½ the 60-cycle loss for the same maximum voltage. Humidity has no effect on the critical voltage or on the loss; smoke lowers the critical voltage and increases the loss; heavy winds have no effect on the critical voltage or on the loss; fog, sleet, rain storms, and snow storms all lower the critical voltage and increase the loss. Snow causes a very marked increase in the loss, as shown by Fig. 26. In calculating *foul weather* loss, make e_o equal to 80 per cent., of the fair weather value.



Kilovolts between Conductors

FIG. 26.—Corona loss during snowstorm.

In calculating corona loss, it must be remembered that the entire line is not at the same potential, and that a small change in e.m.f. above the critical value, e_o, makes a large percentage change in the loss. It has been suggested to make use of this last fact in dissipating energy associated with an abnormal rise of voltage due either to a line surge or to lightning.

The part of the loss curve between E_v and e_o is affected to a considerable degree by the conditions of the wire surface as to dirt, weather, etc., and hence varies from day to day. In practice it is generally not advisable to operate at a higher voltage than that corresponding to e_o (see Table 66), otherwise the loss would become very high during wet weather or when the conductor surface became roughened. Local brushes also occur which may cause deterioration of the conductor by nitric acid formation, especially at the points of support. The voltages in the tables (Par. **66**) correspond to e_o voltages reduced to kilovolts between conductors at 25 deg. cent. and 76 cm. barometer.

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66. Corona limits of voltage. Kilovolts between Conductors (three-phase) at sea level

(Standard)

From formula $e_o = \sqrt{3}\, g_o M_o r \delta \log_e \frac{S}{r}$ where $M_o = 0.87$

A.W.G.	Outside Diam., in.	Spacing—feet									
		3	4	5	6	8	10	12	14	16	20
4	0.230	...	56	58	60	62	64	66	68	69	71
3	0.261	...	62	65	67	70	72	74	76	77	80
2	0.290	...	...	71	73	76	79	81	83	85	87
1	0.330	...	...	79	81	85	88	91	93	95	97
0	0.374	...	...	...	90	95	98	102	104	106	109
00	0.420	...	...	...	98	104	108	111	114	117	121
000	0.470	...	...	...	...	114	118	121	124	127	132
0,000	0.530	...	...	...	...	125	130	135	138	141	146
250,000	0.590	...	...	...	...	138	144	149	152	156	161
300,000	0.620	...	...	...	...	...	151	156	161	165	171
350,000	0.679	...	...	...	...	...	161	166	170	175	180
400,000	0.728	...	...	...	...	...	171	176	180	185	192
450,000	0.770	...	...	...	...	...	178	184	190	194	200
500,000	0.818	...	...	...	...	...	188	194	199	205	210
800,000	1.034	...	...	...	...	...	...	234	241	244	256
1,000,000	1.152	...	...	...	...	...	...	256	264	270	281

(Solid wires) $M_o = 0.93$

A.W.G.	Outside Diam, in.	Spacing—feet									
		3	4	5	6	8	10	12	14	16	20
4	0.204	51	54	56	58	60	62	64	65	66	68
3	0.229	...	59	62	64	66	68	70	72	74	76
2	0.258	...	...	69	70	74	76	78	80	82	84
1	0.289	...	...	75	77	81	83	86	88	90	92
0	0.325	...	...	...	85	89	92	95	97	99	102
00	0.365	...	...	...	94	98	102	105	107	110	113
000	0.410	...	...	...	...	109	113	116	119	121	124
0000	0.460	...	...	...	...	120	125	128	131	134	138

To find the voltage at any altitude, multiply the voltage found above by the δ corresponding to the altitude as given in Par. **67.**

For single-phase or two-phase circuits, find the value of volts for the corresponding three-phase circuit above, and multiply by 1.16.

67. Altitude correction factor δ

Altitude, ft.	δ	Altitude, ft.	δ	Altitude, ft.	δ	Altitude, ft.	δ
0	1.00	2,000	0.92	5,000	0.82	9,000	0.71
500	0.98	2,500	0.91	6,000	0.79	10,000	0.68
1,000	0.96	3,000	0.89	7,000	0.77	12,000	0.63
1,500	0.94	4,000	0.86	8,000	0.74	14,000	0.58

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68. To decrease corona loss, either the frequency or the voltage may be reduced. These, however, are usually fixed. The spacing may be increased, but this decreases the loss but slightly, and the increased conductor spacing would increase the line cost considerably. As the meteorological conditions cannot be controlled, the diameter of conductor must be increased. This may be done without increasing the conductor weight by using aluminum, hemp- or steel-cored cable, or hollow conductors. The use of aluminum and steel-cored aluminum is the most practicable method and in future, it may become necessary to use aluminum for very high voltage lines. Hemp-cored cable has been tired, but the core soon rots and the conductor strands becomes disarranged. Hollow conductors reduce the skin-effect, but the cost of manufacture makes their use prohibitive.

69. Example of calculation of corona loss. Line, 3-phase; length of line, 140 miles; size conductor, No. 4/0 A. W. G. std.; 150 kv. between conductors frequency, 60 cycles; spacing, 14 ft. Assume 20 deg. cent., 76 cm. barometric pressure; coefficient of roughness, $Mo = 0.83$. $\delta = 3.92 \times 76/(273+20) = 1.02$; diameter of wire (Par. 66) 0.530 in.; $r = 0.673$ cm.; $S = 14 \times 12 \times 2.54 = 427$ cm.; $e = 150/\sqrt{3} = 86.6$ kv. to neutral; $g_o = 21.1$ kv. per cm.; $\log_{10} S/r = 2.80$; $e_o = 21.1 \times 0.83 \times 0.673 \times 1.02 \times 2.303 \times 2.80 = 77.5$ kv. to neutral; $P = \frac{344}{1.02} 60 \sqrt{\frac{0.673}{427}} (86.6 - 77.5)^2 \times 1.61 \times 10^{-5} = 1.071$ kw. per wire mile; total corona loss $= 1.071 \times 3 \times 140 = 450$ kw. In practice this loss would not be permissible.

LINE INSULATORS

70. Requirements. The successful operation of a transmission system depends to a large extent upon the degree of insulation attained, and the most important factor is the insulator. Up to a few thousand volts, there is no difficulty whatever in maintaining good insulation, but as the voltage reaches higher values, the difficulties increase and factors such as leakage and capacitive effects, which are entirely negligible in low-tension systems, become of major importance.

Insulators are made of **glass, patented compounds,** and **porcelain.**

71. Glass is cheaper than porcelain and when properly annealed has high dielectric strength and high resistivity. As it is transparent, flaws can readily be detected. On the other hand, moisture condenses on its surface; the action of rain destroys the smoothness of the surface and allows particles of dirt to accumulate, diminishing the resistance of the leakage path. It is easily shattered. Glass is most commonly used for telephone, telegraph and low-voltage insulators.

72. Patented compounds are on the market, having mechanical characteristics practically as good as either porcelain or glass. It is somewhat doubtful, however, if these compounds can successfully withstand the combined effects of weather and the high electrostatic and mechanical stresses incident to high-tension power transmission.

73. Porcelain gives less leakage trouble, is stronger mechanically than glass, and is less affected by changes of temperature. On the other hand, it is more expensive, and slight imperfections in the glaze are common. In its manufacture, underfiring produces good mechanical properties, but tends to cause porosity in the porcelain, which almost always results in rapid deterioration and failure when in service. Over-firing minimizes porosity, but makes the porcelain brittle. Close control of the kiln temperature has greatly improved the quality of porcelain. Porcelain has a tensile strength of about 1,500 lbs. per sq. in. and a compressive strength of about 40,000 lbs. per sq. in. As porosity and flaws, such as blow-holes, cracks, and the like, cannot be detected readily by simple inspection, each section should be subjected to a voltage test before and after assembling. Because of its superior characteristics, porcelain is used almost universally for high-voltage insulators.

74. Pin-type insulators are designed to operate up to 90,000 volts, but are seldom used for voltages in excess of 70,000 volts. In the past it has been found difficult to vitrify porcelain properly if the thickness was too great. Therefore, high-voltage insulators are made up of shells of moderate

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thickness, cemented together with neat Portland cement, as shown in Fig. 29, each shell operating at about 15,000 volts.

75. Insulators have appreciable capacitance (of the order of 2×10^{-11} farad), and act like condensers of complicated construction. The dielectric is made up of alternate layers of air and porcelain or glass of varying thicknesses. Some of the charging current to the pin must pass over the surface of the insulator, which has a very high resistance, so the insulator may be represented by a resistance, shunted by a number of small condensers, as shown in Fig. 27. E is the voltage from the line to the pin, I the total current taken by the insulator, i_c the charging current of each of the shunted con-

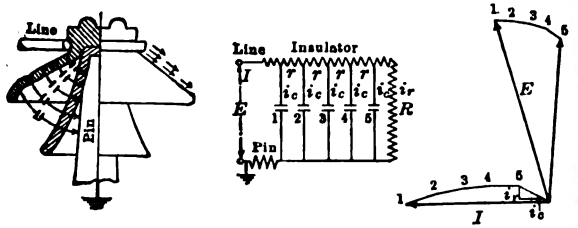


FIG. 27.—Insulator, equivalent circuits.

denser, and i_r the leakage current. The vector diagram merely illustrates the theory, and no attempt has been made to give the proper relative values to the various quantities. As the ohmic resistance of porcelain insulators is extremely high, most of the leakage occurs over the surface.

The minimum arcing distance and leakage path are shown in Fig. 28, as ABC, and ab, respectively. That part of the leakage path on the top of the cap and on the outer side of the petticoats often becomes conducting, due to rain, salt fogs, accumulated dirt, etc. The resistance is directly proportional to the length and inversely proportional to the sectional area of the path, so that beyond a certain point increasing the diameter of the petticoats

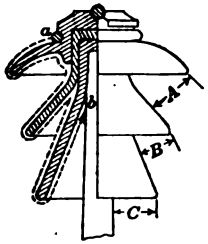


FIG. 28.—Arcing and leakage paths.

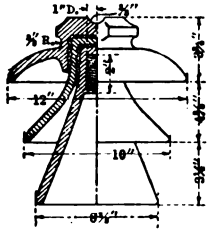


FIG. 29.—Pin-type insulator.

does not increase the leakage resistance appreciably. Increasing the number of petticoats increases the length of path without necessarily increasing the area, so that a high leakage resistance is best secured by increasing the number of petticoats. The fact that porcelain has a permittivity of between 4 and 5 tends to produce larger proportionate dielectric stresses in the air spaces, with the result that corona tends to form, reducing the arcing distance and the leakage path.

76. A *high efficiency insulator design has been developed on scientific principles by G. I. Gilchrest. In order to reduce corona, to decrease

*A. I. E. E. *Trans.*, Vol. XXXVII, 1918, page 805.

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the impulse ratio (see Par. **80**), to increase the arcing-over voltage, and the mechanical strength under electric stress, the insulator, Fig. 30, is constructed with the following features: (1) Surfaces *a* conform to the flow lines of the electrostatic field; (2) Surfaces *b* of the rain sheds conform to the equipotential surfaces; (3) lines of mechanical stress are parallel to the electrostatic stress lines; (4) the leakage resistance per shell is nearly constant, but is decreased gradually from the head to the center shell; (5) the capacitance is approximately the same for each shell.

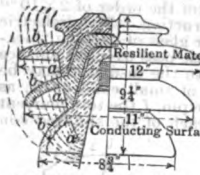


FIG. 30.—High efficiency insulator with electrostatic field.

77. Suspension insulators under favorable conditions can be operated at an average voltage of about 20,000 volts per unit. They are used almost exclusively for transmission voltages in excess of 70,000, as the pin-type insulator then becomes excessively large, heavy, expensive, and mechanically weak. When suspension insulators are used, the cost and weight are practically proportional to the line voltage, but beyond a certain point it is difficult to secure increased insulation even with additional units (see Par. **78**). There are two common types: In the Hewlett, or interlinking type, Fig. 31(*a*), the two suspension cables loop through each other and are separated by a layer of porcelain. In the cemented type, the porcelain or glass is cemented into a metal cap, and the pin is cemented into the insulator. Fig. 31(*b*) shows a one-piece cemented unit and Fig. 32 shows a

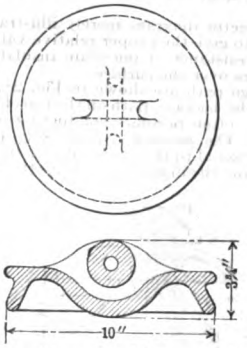


FIG. 31*a*.—Hewlett suspension insulator.

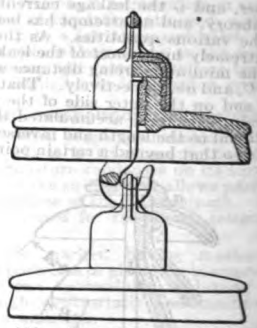


FIG. 31*b*.—One-piece cemented insulator, suspension type.

two-piece cemented unit. The Hewlett type is used extensively for strain insulators. It has the advantage of not being cemented in a metal cap. The units are joined together by looped cables and by clamps. It is probably more difficult to replace than the cap and pin type. The cable holes should be filled with cement in order to prevent water entering and then freezing. The cemented type has given trouble, due to failures at the base of the cap, and in design this factor should be carefully considered. The present tendency in insulator design is toward smaller discs and closer spacing. This results in higher puncture strength for a given flash-over voltage. Fig. 33 shows the relation of the sizes and weights of insulators to their normal rating.

78. The string efficiency of *n* suspension-insulator units is the ratio of their total flash-over voltage to *n* times the flash-over voltage of one insulator. Although certain unpublished 500,000-volt tests have shown this ratio to be practically unity, the majority of experiments show that the

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string efficiency decreases when the number of insulators is increased. Fig. 34 shows the results of the tests made by F. W. Peek, Jr.* This lowering of flash-over voltage is due to the fact that each insulator has a certain capacitance to ground, the insulator nearest the line carrying the charging current of the whole string of n insulators. The second insulator carries the charging current of $n-1$ insulators, etc., so the unit next the line is subjected to the greatest stress, the second unit to a lesser stress, etc. In a string of 7 insulators, the voltage across the line insulator may be easily twice that across the cross-arm insulator. The string efficiency is nearer unity under the wet test, as the leakage current is then so increased that the effect of the capacitive current is negligible. The string efficiency is increased by making the ratio of mutual capacitance to ground capacitance large; that is, by hanging the insulator units near together but having each string at some distance from the pole or tower.

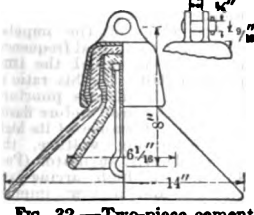


FIG. 32.—Two-piece cemented insulator, suspension type.

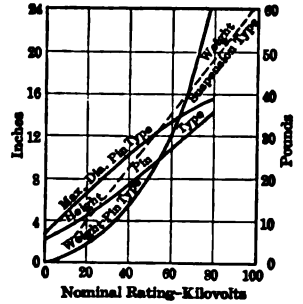


FIG. 33.—Weights and sizes of insulators.

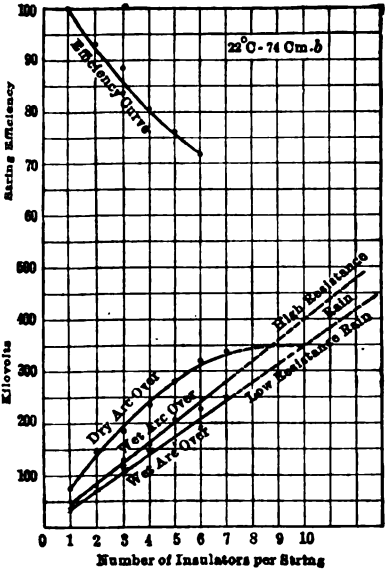


FIG. 34.—Insulator string efficiency.

79. Strain insulators are used when the line is dead-ended; at intermediate anchor towers; on sharp curves where the line would tend to overturn the insulator, break the pin, or pull a string of suspension insulators out of alignment; and on extra long spans, as at river crossings. For voltages up to 30,000, a pin-type insulator may be used. For voltages in excess of 30,000, either the link-type (Fig. 31a) or the cemented type (Fig. 32) is used.

* Peek, F. W. Jr., "Electrical Characteristics of the Suspension Insulator." *Trans.* A. I. E. E., Vol. XXXI, 1912, p. 907.

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80. *Effect of high frequency on insulators. Insulators that only flash over at commercial frequencies may puncture at the same voltage if the frequency be high. This is probably due in part to the altering of stress distribution caused by the change in the ratio of susceptance to leakage conductance brought about by high frequency. It is also due in part to the corona not having time to form and relieve the stress by rupture of the air. To prevent puncture due to high frequency disturbances, the ratio of puncture voltage to flash-over voltage should be high.

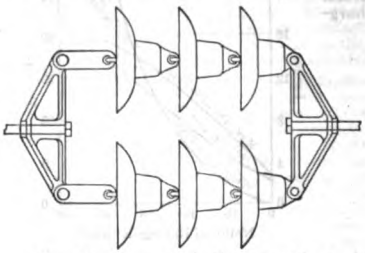


FIG. 35.—Strain insulator with yoke.

The ratio of the impulse flash-over to normal frequency flash-over is called the **impulse ratio.** If this ratio is too high, insulators puncture through the head before flashing over. Because of its high corona-forming voltage, the Jeffery-Dewitt insulator (Par. **85**) has a high arcing-over voltage and a low impulse ratio. The unusual thickness of porcelain prevents puncture through the head in this type. Therefore some engineers favor a high impulse ratio and some favor a low impulse ratio. Insulators having high impulse ratios should also have high puncture voltages.

81. Insulator testing is of two kinds, design tests and routine tests. Design tests cover those features that are important to the purchaser, such as dry and wet flash-over, puncture voltage, tensile strength, and are usually made on the assembled unit or string. The insulator should be tested under conditions approximating those attained in service, such as mounting or suspending from a grounded pin and cross arm, well away from other objects. The potential should be applied between the pin and a short length of cable, representing the line conductor, tied or clamped to the insulator. The standard wet test is to spray water over the insulator at an angle of 45 deg. and at a precipitation rate of 0.2 in (0.508 cm.) of water per min. As results are largely dependent on the electrolytic nature of the water, distilled water is to be preferred, as more uniform results are obtained

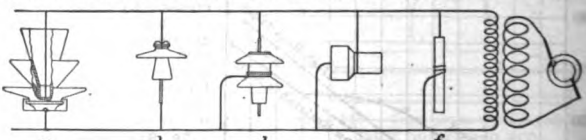


FIG. 36.—Insulator testing.

by its use. Insulators, under ordinary conditions, flash over before puncturing, so in order to obtain the puncture voltage, the insulators must be immersed in oil.

Routine tests should be made on each part of every insulator before assembling, and also on the complete unit. The object is not to flash over the insulator but rather to detect existing faults before the insulator is put in service. The parts of pin and suspension type insulators are inverted in water, thus forming one terminal. Water is also placed inside the insulator covering the threads in the threaded parts, and from 0.5 to 0.75 in. (1.27 to 1.9 cm.) deep in the other parts, thus forming the other terminal as shown in a, Fig. 36. Dry tests are often made on the assembled unit, b, c, d, e (Fig.

* Imlay, L. E., and Thomas, Percy H. "High Frequency Tests of Line Insulators." *Trans.* A. I. E. E., Vol. XXXI (1912), p. 2121.

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36) and are necessary on strain insulators and bushings. *Free arcing tests* are obtained when the testing transformer has sufficient capacity to maintain a heavy power arc after flash-over occurs. The *breakdown voltage of insulators* is a function of the time during which the voltage is applied, as has been shown by A. O. Austin.* A higher potential for a short time will eliminate poor insulators in the same manner as a lower potential for a longer time. Such curves for 100 kv. and 85 kv. are shown in Fig. 37. Thus 100 kv. for one-half minute will eliminate 2.2 per cent., whereas 85 kv. must be applied 4.7 minutes to produce the same result.

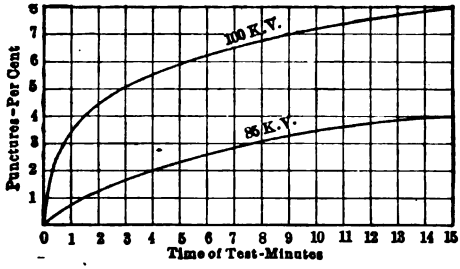


FIG. 37.—Insulator time-puncture curves.

Defective parts may also be detected by high frequency tests and by the use of a megger. The megger tests may lead to erroneous conclusions, particularly if the insulator is dry. Insulators when sound should test about 3×10^8 megohms. Insulators testing below 2,000 megohms are probably defective.

82. Faulty insulators may be detected by removing them from the line and testing them by the methods given in Par. **81**. Methods have been developed whereby faulty units of a string or faulty parts of a pin insulator may be detected without interrupting the service. These methods depend either upon the lowered voltage across the faulty section or the hissing sound made by the discharge across a fault. In the †"buzz-stick" method, the faulty unit is detected by the appearance and sound of the arc obtained when a U-shaped discharger is touched and withdrawn from each section. The faulty unit is finally located by actually short-circuiting it if there are not too many defective parts to the insulator. In the "spark stick" method, the insulator unit is shunted by an adjustable gap in series with a condenser of about one-fourth the capacitance of the insulator unit. A faulty section is also detected by the sound of the arc made when the gap is closed and then opened. ‡Faulty insulators may also be detected by hissing sounds heard in telephone detectors, which either shunt some of the leakage current from a wooden pole or else are actuated by the discharge current to an antenna mounted on a wooden stick and held near the insulator.

83. Deterioration. Insulators deteriorate rapidly after being in service for some time. There are many theories as to the reason for this, among them being porosity of the porcelain thus admitting moisture; brittleness due to over-firing; combined electrical and mechanical stresses; cracks produced by sudden changes in temperature; and mechanical stresses due to the fact that the rim cap, the porcelain and the cement have unequal temperature coefficients of cubical expansion. Also, the cement hydrates for a long time after it is supposedly set, which increases its volume and stresses the porcelain. Experiment indicates that the last three causes

*Austin, A. O. "The High-Efficiency Suspension Insulator." *Trans.* A. I. E. E., Vol. XXX (1911), p. 2303.

† *Electric World*, Vol. 74, 1919, page 568.

‡ Flaherty, B. G. "Testing for Defective Insulators On High-tension Transmission Lines." *Trans.* A. I. E. E., Vol. XXXV (1916), p. 1095.

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are accountable for the greatest number of failures. Some* comp ies now use resilient material between the tops of the caps (Fig. 30) and nd

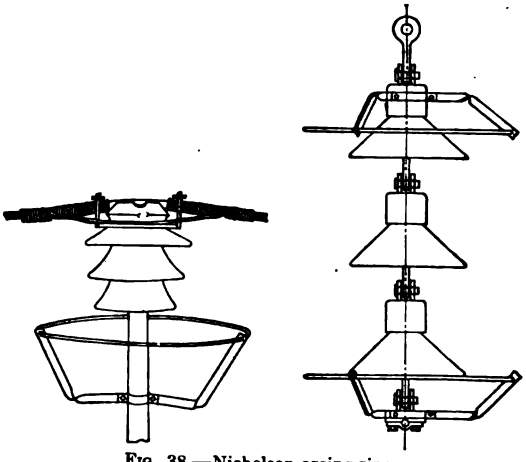


FIG. 38.—Nicholson arcing rings.

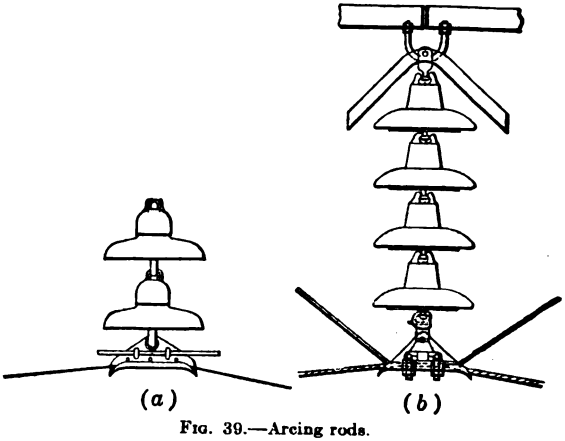


FIG. 39.—Arcing rods.

the surfaces between insulator sections in order to reduce these mechar al stresses.

* Austin, A. O. "Present Practice in the Design and Manufactur of High-tension Insulators." *Trans.* A. I. E. E., Vol. XXXVI (1917), p. 5; see p. 554.

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84. Arcing rings. Insulator petticoats are often shattered by the power arc following a flash-over. At the same time the line conductors may be burnt off by this same arc. To protect both the insulator and the line, arcing rings, Fig. 38, arcing rods, Fig. 39, and the Thomas line protector, Fig. 40, are used. These devices hold the arc away from the insulator, and also prevent its burning off the line wire.

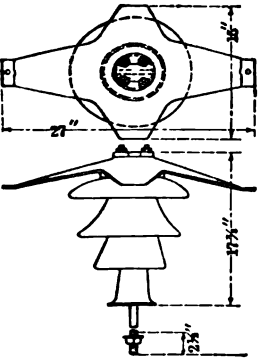


FIG. 40.—Thomas line protector.

85. The *Jefferey-Dewitt Suspension Insulator, Fig. 41, differs from the conventional types in that the porcelain is in tension rather than in compression and shear. To eliminate the stresses occasioned by the unequal expansion of the metal and the porcelain, the usual cap is replaced by a semi-flexible, pressed-steel spider, set into the porcelain and held by an alloy having practically the same coefficient of cubical expansion as the porcelain. Other features claimed for this insulator are that the surface gradient is nearly uniform, resulting in high corona-forming voltage (60,000 volts), and high flash-over voltage (100,000 volts). The thickness of the porcelain minimizes the possibilities of the insulator being shattered by power arcs, or by rifle shots and in addition gives a puncture voltage of 300,000 volts. By a special process, and by the use of a continuous tunnel kiln, it is possible to produce the thick porcelain of this insulator without firing cracks, porosity, etc. The insulator develops a tensile strength of about 9,000 lbs.

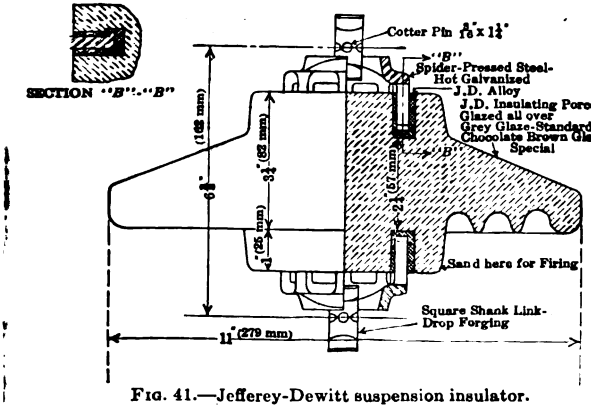


FIG. 41.—Jefferey-Dewitt suspension insulator.

SYSTEM CONNECTIONS AND SWITCHING

86. System connections should be made in such a manner that continuity of service, flexibility, and safety are secured without undue complications of wiring and switching.

87. Duplicate lines are usually necessary, where continuity of service is important. It is customary to run the two lines on the same poles or towers, especially if these are of steel or concrete, as the total cost of line supports is then much less than it would be for two individual pole lines.

* Peaslee, W. D. "Factors Controlling the Design and Selection of Suspension Insulators." *Trans. A. I. E. E.*, Vol. XXXIX (1920), p. 1645.

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Where the power is especially valuable, the two lines may be run over t
different routes, removed from each other. This lessens the chance of b
lines being disabled at the same time by lightning or by other natural caus
The cost of two such lines is frequently prohibitive. When it is necess
to shut down a line for repairs, the service is interrupted if two lines
not available. Where the regulation would be impaired, or the overl
capacity of one line is not sufficient to carry the entire load during suc
shut-down, sectionalizing switches may be provided. The section requir

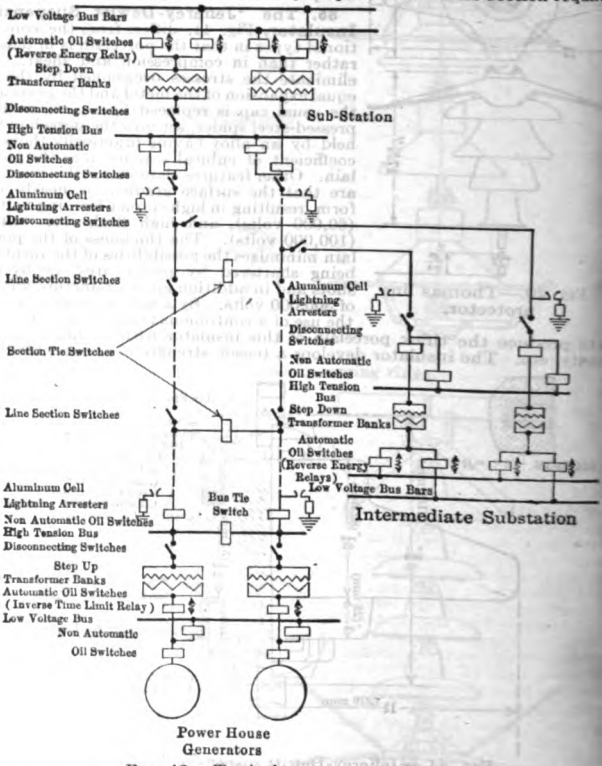


FIG. 42.—Typical system connections.

repairs may be isolated and grounded, the two lines being in parallel for t
remaining distance. This insures better and more continuous service, thou
frequently the advantage gained is more than offset by the added expense a
switching complication. Fig. 42 shows the connections for a typical pow
system.

88. Substation connections are made as shown in Fig. 42 and Figs.
and 79. See also Sec. 10 and Sec. 12.

89. Advantages of grounded systems are as follows: (a) Exce
under unusual transient conditions, the voltage from line wire to grou
never exceeds the Y voltage, so the line insulation need not have so large
factor of safety as with isolated systems; (b) a ground on one wire opens t

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breakers and warns the operator of trouble; (c) the dynamic arc to ground has but little tendency to create high frequency oscillations; (d) disturbances to the telephone system due to electrostatic unbalancing are a minimum.

90. Disadvantages of grounded systems are: (a) The line is inoperative if a ground occurs; (b) the short-circuit current may produce strong mechanical forces in generator and transformer windings, causing serious damage; (c) the dynamic arc may shatter the insulators or burn off the conductors, because of the large amount of energy available; (d) inductive effects of the earth current may affect the telephone and telegraph circuits, though the earth current is practically negligible except in case of an accidental ground.

91. Conditions of advantageous grounding. A system in excess of 30,000 volts may well be grounded, unless absolute continuity of service is essential. A line connected as a part of a large system should be grounded. It will then be automatically disconnected and cannot subject the entire system to the delta voltage between line wire and ground. A cable system should be grounded, as oscillations and transients are of common occurrence, and a ground in one part of the system may otherwise cause a breakdown in the insulation at some other point. To locate and repair a ground in a cable system is expensive, requiring considerable time.

92. The ground connection may be made by connecting the neutral to a copper plate buried in charcoal; by connecting to a metal plate immersed in a nearby body of water; by connecting to metal work in contact with the earth or water; by driving iron pipes of about 1 in. (2.54 cm.) or so in diameter and 6 ft. (2 m.) in length into the earth 6 ft. (2 m.) apart, and pouring salt water around them. To limit the short-circuit current, a resistance may be inserted in the neutral connection, though to secure one having the necessary resistance and carrying capacity is expensive. A reactance should not be used in the neutral as it may increase the probability of oscillations. The ground should be made at only one point of the system, at the power-house, as otherwise earth currents, particularly those of triple harmonic frequency and multiples thereof, tend to flow and to disturb telephone and telegraph circuits in the vicinity of the line.

93. Ungrounded systems have the following advantages: (a) an accidental ground does not shut down the system; (b) the earth may serve as a third conductor until the damage can be repaired; (c) an arcing ground may be cleared by the arcing ground suppressor; (d) under normal conditions, there is little effect on telephone and telegraph lines.

94. Disadvantages of ungrounded systems are as follows: (a) Though the neutral of the system should be at ground potential, experiment has shown that excessive voltage may exist between neutral and ground; (b) the insulation of the system must be designed to withstand the delta voltage, and therefore must have 1.7 times the insulation for the same factor of safety; (c) an arc to ground is in series with the line capacitance, and therefore tends to set up destructive high-frequency oscillations; (d) any electrostatic unbalancing affects neighboring telephone and telegraph systems.

95. Ungrounded systems should be used where the voltage is moderate; where a shut-down would be a serious matter; where the apparatus may well withstand the full-line potential.

96. Transformer connections may be either delta or star. Transformers connected in delta must be able to withstand the total voltage between lines, hence their cost is greater than for star-connected transformers. They are more reliable than the star-connected, for if one transformer is disabled, the system will continue to operate connected open delta. Transformers connected in delta may be heated by the third harmonic circulatory current. The star connection affords an accessible neutral, and the transformers need be designed to withstand only 58 per cent. of the line voltage. There is no third-harmonic circulatory current possible, and any third-harmonic voltage does not appear on the line. If one transformer goes out, the system must either be operated single-phase, or be shut down, unless a spare unit is available. Voltage taps are easily brought out from the transformer winding in the star connection. See Sec. 6.

97. Switching a transmission line always gives rise to transients which usually attenuate rapidly and die out without damage to the system. Under favorable conditions, however, transients caused by switching often result in serious damage to line and apparatus. The matter is further

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complicated by the characteristics of the oil switches themselves. When t switch contacts approach each other on closing the circuit, small arcs decreasing magnitude are set up between them. These may result in hi frequency oscillations corresponding in period to the natural frequency of t transformer windings. In a three-phase switch the three contacts may n close at the same instant which further complicates the problem. Simil phenomena occur when the switch opens the circuit, the arcs between co tacts increasing in magnitude. The maximum possible voltage rise the switch opens is given by

$$e = i\sqrt{L/C}$$

where i is the current at the moment of break and L and C are the circ inductance and capacitance respectively. The voltage does not usually a proach this limiting value, as the arcs formed between the contacts introdu resistance which diminishes the voltage rise. The switch also absorbs so of the energy stored in the line. The voltage rise, under ordinary switchi conditions, may not exceed the normal operating value by more than from to 75 per cent. The excessive rises in potential occur under short-circ conditions, when the current may reach many times full-load valu Aluminum arresters and power-limiting reactances offer the best soluti of the problem.

98. High-tension and low-tension switching are both extensive employed, there being no consensus of opinion as to which is more desirab The following methods are used in switching on a substation.

(a) Connect the line to the high-tension bus at the generating station, a then switch the substation transformers.

(b) Connect substation transformers to the dead line, and then swit the line to the high-tension bus at the generating station.

(c) Connect the open line to the transformers at the generating statio switch these on the low side, and then connect the substation transformers the end of the live line.

(d) Connect the substation transformers to the dead line and step t transformers and switch these latter on the low-tension side.

(a) and (b) come under the classification of high-tension switching and (and (d) low-tension switching. The reverse order may be followed, wh switching off.

(b) and (d) are not desirable methods, as the potential waves which s first sent out along the line are reflected at nearly double amplitude at t receiving end which puts high voltage stresses across the transformers a other apparatus connected at the receiving end of the line.

Transformer switching may result in abnormal current rushes, if the circ is closed on a point of the e.m.f. wave which does not correspond to t residual magnetic state of the transformer.

POWER-FACTOR CORRECTION

99. Power-factor correction may often be made on transmission lin whereby the voltage regulation may be materially improved, the generati capacity increased and the copper losses reduced. This correction may made by the over-and the under-excitation of synchronous apparatus at t receiving end of the line. When used for this purpose exclusively, suc apparatus is called a synchronous condenser. This synchronous apparatu may be a part of the receiver and used for further distribution of power, o it may merely float on the end of the line, its sole function being to regula the power-factor, or the voltage. As synchronous motors are not woun for voltages much in excess of 13,000 volts, they must be connected to t low sides of transformers if the line voltage exceeds this value. When t motor is installed solely to improve transmission efficiency, the cost of t power required by the motor, plus its maintenance and fixed charges, mu not exceed the cost of the power saved, and must be less than the interest o the cost of installing more copper. As the synchronous apparatus may fa out of step, or be damaged by surges or short-circuits, it is generally desirab to install copper, which will give greater reliability, and has a better scra value.

When improved regulation is the result desired, the installation of sy chronous apparatus may be justified regardless of the energy saving. Whe large amounts of power are concerned, it is impracticable to install synchrono condensers to take care of the entire quadrature current, although they ma be used for purposes of improved regulation. In the 150,000 volt, 140-mi line which runs from Big Creek, Cal. to Los Angeles, two 15,000 kv-a. sy

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chronous condensers are installed in Los Angeles merely for controlling the voltage at the receiving end of the line.

100. Calculations for power-factor correction. The per cent. quadrature current required for unity power-factor at the receiver may be determined from **Fig. 41**, or may be calculated for a three-phase system as follows:

$$I_1 = \frac{P}{3E} \tag{33}$$

$$I_2 = \frac{P}{3E} \tan \theta \tag{34}$$

where I_1 and I_2 are the energy and quadrature components of current respectively, P is the power, in watts, at the receiver, E is the voltage from line wire to *neutral*, at the receiver, and θ is the angle between the current and voltage vectors. It will be noted, from Fig. 43 that it requires a much larger synchronous motor to bring the power-factor from 95 per cent. to 100 per cent., than is required to bring it from 90 per cent. to 95 per cent. As a rule, it is not economy to install apparatus large enough to obtain the last 5 per cent.

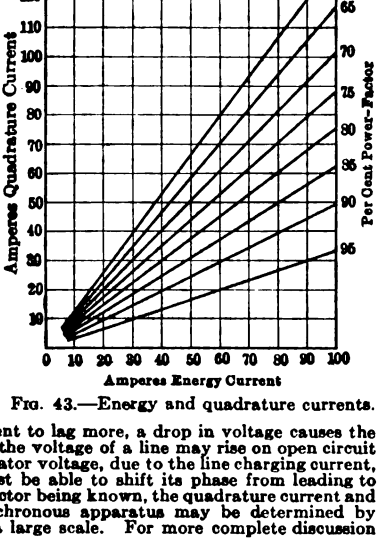


FIG. 43.—Energy and quadrature currents.

101. Constant receiver voltage* may be obtained by varying the excitation of the synchronous apparatus, either by use of an automatic regulator which acts on the exciter or by compounding, if the synchronous apparatus is a motor-generator or a rotary converter. When the variations in voltage are not severe, hand regulation may be employed. Machines cannot always be compounded to give constant voltage at all loads, though the condition of constant voltage may be approximated. Without any regulation whatsoever, synchronous apparatus tends to maintain constant voltage at the end of a line. A rise in voltage at the terminals causes the current to lag more, a drop in voltage causes the current to lead more, etc. As the voltage of a line may rise on open circuit to a value in excess of the generator voltage, due to the line charging current, the synchronous apparatus must be able to shift its phase from leading to lagging current. The power-factor being known, the quadrature current and the required capacity of synchronous apparatus may be determined by plotting Fig. 17 (Par. **28**) to a large scale. For more complete discussion consult the bibliography.

STRESSES IN SPANS

102. Mechanical stresses in a span are produced by: (a) the dead weight of the conductor, which acts vertically; (b) the weight of any ice, sleet, or snow that may cling to the wire; and (c) the wind pressure, which is assumed to act horizontally, at right angles to the line, and on the projected area of the conductor and its sleet loads.

The weights of copper and aluminum conductors are given in Par. **104**. The weight of ice is 57 lb. per cu. ft., or 0.033 lb. per cu. in., and the weight of sleet and snow is somewhat less than this. For the average climate of the United States, a layer of ice 0.5 in. (1.27 cm.) thick is assumed to be the worst condition of loading, though in the mountainous regions, sleet may form to a greater thickness than this. The table in Par. **104** gives the ice and conductor

* Bibliography 37.

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loads with 0.5-in. and 0.75-in. layers of ice, for both copper and aluminum conductors.

The wind pressure is a function of the wind velocity and may be expressed by Buck's* formula

$$p = 0.0025V^2 \qquad \text{(lb. per sq. ft.)} \qquad (35)$$

Where p is the pressure in lb. per sq. ft. and V is the actual velocity of the wind in miles per hr. Fig. 44 shows the relation between velocity and wind pressure. Buck gives the following as the relation between actual velocity and that indicated at the Government observation stations.

Indicated velocity...	10	20	30	40	50	60	70	80	90	100
Actual velocity.....	9.6	17.8	25.7	33.3	40.8	48.0	55.2	62.2	69.2	76.2

Fig. 45 shows the wind pressure at different heights above ground, and Par. **104** gives the pressure for the various conductors and ice loads.

The resultant force acting on the conductor is the vector sum of the horizontal and vertical forces shown in Fig. 46. The resultant loading for various conditions of component loading on line conductors is given in Sec. 6

103. The general span formulæ, assuming that the span has the form of a parabola and that the weight is uniformly distributed, are as follows:

$$t = \frac{S^2 w}{8d} \qquad \text{(lb.)} \qquad (36)$$

$$d = \frac{S^2 w}{8t} \qquad \text{(ft.)} \qquad (37)$$

$$l = S + \frac{8d^2}{3S} \qquad \text{(ft.)} \qquad (38)$$

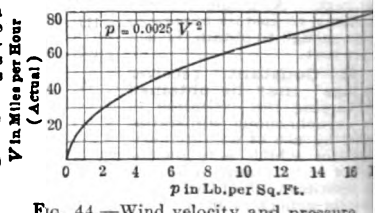


FIG. 44.—Wind velocity and pressure.

where t is the horizontal tension in lb., S is the span length in ft., d the sag in ft., w is the weight in lb. per ft. of the conductor plus the sleet and snow, and l is the length of the conductor in ft. The total tension T in the conductor at the support, is the sum of the horizontal component t, and the vertical component due to the dead load.

$$T = t + wd \qquad \text{(lb.)} \qquad (3$$

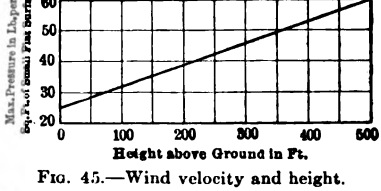


FIG. 45.—Wind velocity and height.

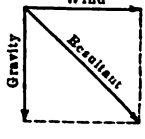


FIG. 46.—Resultant force on the wire.

The second term is usually very small, and for ordinary sags is negligible. If in Eq. 37 the conductor is considered by itself, ignoring sleet and wind loads, then

$$d = \frac{S^2\left(\frac{w}{A}\right)}{8\left(\frac{t}{A}\right)} = \frac{S^2 W}{8F} \qquad \text{(ft.)} \qquad (4$$

where W is the weight of the conductor per ft. of length and for 1 sq. in. cross-section, and F is the tension in lb. per sq. in. The required deflection may then be determined for the allowable unit stress.

* Fowle, Frank F. "A Study of Sleet Loads and Wind Velocities." *Elec. World*, Vol. LVI (1910), p. 995.

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Copper wire—stranded

Cir. mils and A.W.G.	Diam., inches	Area, sq. in.	Hard drawn		Soft drawn		Load per lin. foot, vertical			Load per lin. foot, horisontal			Max. load per lin. foot, plane of resultant			EA	
			Ultimate tension, lb.	Allow. tension	Ultimate tension, lbs.	Allow. tension	Dead	Dead + ½ in. ice	Dead + ¾ in. ice	16.0 lb. p. sq. ft.	8.0 lb. p. sq. ft., ½ in. ice	11.0 lb. p. sq. ft., ¾ in. ice	Class A load'g	Class B load'g	Class C load'g	E(hard drawn) 16,000,000	E(annealed 12,000,000
500,000	0.819	0.3924	23,540	11,750	13,340	6,650	1.525	2.345	2.989	1.024	1.213	2.126	1.837	2.640	3.668	6,278,400	4,708,800
350,000	0.679	0.2750	16,500	8,250	9,350	4,650	1.068	1.801	2.401	0.849	1.119	1.997	1.364	2.120	3.123	4,400,000	3,300,000
0.000	0.530	0.1662	9,970	5,000	5,650	2,800	0.645	1.286	1.831	0.663	1.020	1.861	0.925	1.641	2.611	2,659,200	1,994,400
000	0.470	0.1318	7,910	3,950	4,480	2,250	0.513	1.116	1.651	0.588	0.980	1.806	0.780	1.485	2.446	2,108,800	1,581,600
00	0.420	0.1045	6,270	3,150	3,555	1,750	0.406	0.978	1.498	0.525	0.947	1.760	0.664	1.361	2.311	1,672,000	1,254,000
0	0.375	0.0829	4,970	2,500	2,820	1,400	0.322	0.866	1.372	0.469	0.917	1.719	0.569	1.261	2.199	1,326,400	994,800
1	0.330	0.0657	3,940	1,950	2,235	1,100	0.255	0.771	1.263	0.413	0.887	1.678	0.485	1.175	2.100	1,051,200	788,400
2	0.291	0.0521	3,130	1,550	1,770	900	0.203	0.695	1.174	0.364	0.861	1.642	0.417	1.107	2.019	833,600	625,200
3	0.261	0.0413	2,480	1,250	1,405	700	0.160	0.633	1.103	0.326	0.841	1.614	0.363	1.053	1.955	660,800	495,600

Copper wire—solid

0000	0.460	0.1662	8,310	4,150	5,650	2,800	0.641	1.238	1.770	0.575	0.973	1.797	0.861	1.575	2.522	.....	.....
000	0.410	0.1318	6,590	3,300	4,480	2,250	0.509	1.074	1.591	0.512	0.940	1.750	0.722	1.427	2.365	.....	.....
00	0.365	.1045	5,220	2,600	3,555	1,750	0.403	0.940	1.443	0.456	0.910	1.709	0.608	1.309	2.237	.....	.....
0	0.320	0.0829	4,560	2,300	2,820	1,400	0.320	0.833	1.323	0.406	0.883	1.673	0.517	1.214	2.133	.....	.....
1	0.289	0.0657	3,740	1,850	2,235	1,100	0.253	0.744	1.223	0.362	0.860	1.640	0.442	1.137	2.046	.....	.....
2	0.258	0.0521	3,120	1,550	1,770	900	0.202	0.673	1.142	0.322	0.838	1.611	0.380	1.075	1.975	.....	.....
3	0.229	0.0413	2,480	1,250	1,405	700	0.159	0.613	1.073	0.287	0.820	1.585	0.328	1.024	1.914	.....	.....
4	0.204	0.0328	1,960	1,000	1,115	550	0.126	0.564	1.016	0.255	0.803	1.567	0.284	0.981	1.863	.....	.....
5	0.182	0.0260	1,560	800	885	450	0.100	0.524	0.969	0.227	0.788	1.542	0.248	0.946	1.821	.....	.....
6	0.162	0.0206	1,240	600	700	350	0.079	0.491	0.930	0.203	0.775	1.524	0.218	0.917	1.785	.....	.....

NOTE: Class A loading = dead load + 15.0 lb. per sq. ft. wind pressure. E = modulus of elasticity, in.-lb.
Class B loading = dead load + 0.5 in. ice + 8.0 lb. wind pressure. A = conductor area.
Class C loading = dead load + 0.75 in. ice + 11.0 lb. wind pressure. EA = product of modulus of elasticity and conductor area.

* Report of the Joint Committee on Overhead Line Construction, N. E. L. A., May, 1911. Page 411. Vol. II.

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104. Loading tables. —(*Continued*)

Aluminum wire—stranded

Cir. mils and A.W.G.	Diam., inches	Area, sq. in.	Hard drawn: Ultimate tension, lbs.	Hard drawn: Allow. tension	Soft drawn: Ultimate tension, lbs.	Soft drawn: Allow. tension	Load per lin. foot, vertical: Dead	Dead + ½ in. ice	Dead + ¾ in. ice	Load per lin. foot, horizontal: 15.0 lb. p. sq. ft.	8.0 lb. p. sq. ft., ½ in. ice	11.0 lb. p. sq. ft., ¾ in. ice	Max. load per lin. foot, plane of resultant: Class A load'g	Class B load'g	Class C load'g	*EA* (*E* = 9,000,000) (stranded): E (hard drawn) 16,000,000	E (annealed) 12,000,000
500,000	0.814	0.3924	9,025	4,500	.....	.....	0.460	1.280	1.919	1.018	1.209	2.121	1.117	1.762	2.860	3,531,600	
350,000	0.679	0.2750	6,325	3,150	.....	.....	0.322	1.055	1.655	0.849	1.119	1.997	0.908	1.538	2.594	2,475,000	
0000	0.522	0.1662	3,820	1,900	.....	.....	0.195	0.831	1.382	0.652	1.015	1.853	0.681	1.312	2.312	1,495,800	
000	0.464	0.1318	3,160	1,600	.....	.....	0.155	0.755	1.288	0.580	0.976	1.800	0.600	1.234	2.213	1,186,200	
00	0.414	0.1045	2,510	1,250	.....	.....	0.122	0.691	1.208	0.518	0.943	1.754	0.532	1.168	2.130	940,500	
0	0.368	0.0879	1,990	1,000	.....	.....	0.097	0.637	1.140	0.460	0.912	1.712	0.470	1.112	2.057	746,100	
1	0.328	0.0657	1,575	800	.....	.....	0.077	0.592	1.082	0.410	0.885	1.676	0.417	1.065	1.995	591,300	
2	0.291	0.0521	1,250	600	.....	.....	0.061	0.533	1.032	0.364	0.861	1.642	0.368	1.023	1.939	168,900	
3	0.261	0.0413	990	500	.....	.....	0.049	0.522	0.992	0.326	0.841	1.614	0.329	0.990	1.894	371,700	
4	0.231	0.0328	790	400	.....	.....	0.039	0.494	0.954	0.289	0.821	1.587	0.292	0.958	1.846	295,200	

Galvanized steel wire—stranded

Diam. in.	No. and gauge of wires	Area sq. in.	Ultimate strength (lb.): Guy wire	Siemens Martin 75,000	High tension 125,000	Ex. high tension 187,000	Load per lin. ft., vertical: Dead	Dead + ½ in. ice	Load per lin. ft. horizontal 8.01 lb. per sq. ft. ½ in. ice	Max. load per lin. ft., of resultant class *B* loading	*EA* *E* = 29,000,000
5/8	7–5	0.2356	.....	19,000	25,000	42,000	.....	.....	1.083	.....	6,832,000
9/16	7–6½	0.1922	.....	14,500	21,000	34,500	0.668	1.329	1.042	.....	5,574,000
½	7–8	0.1443	8,500	11,000	18,000	27,000	0.510	1.132	1.000	1.510	4,185,000
7/16	7–9	0.1204	6,500	9,000	15,000	22,500	0.415	0.998	0.958	1.383	3,492,000
3/8	7–11	0.0832	5,000	6,800	10,500	17,250	0.295	0.839	0.917	1.243	2.413,000
5/16	7–12	0.0606	3,800	4,860	8,100	12,150	0.210	0.715	0.875	1.130	1,757,000

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105. Stress at centre of span resulting from a given deflection

Deflection in decimal part of span

Span in ft.	0.001	0.002	0.005	0.010	0.015	0.020	0.030	0.040	0.050	0.060	0.070
	Multiplier										
10	1,250.001	625.003	250.008	125.016	83.358	62.533	41.716	31.316	25.083	20.933	17.973
20	2,500.003	1,250.006	500.016	250.033	166.716	125.066	83.433	62.633	50.166	41.866	35.947
40	5,000.006	2,500.013	1,000.033	500.066	333.433	250.133	166.866	125.266	100.333	83.733	71.895
50	6,250.008	3,125.016	1,250.041	625.083	416.791	312.666	208.583	156.583	125.416	104.666	89.869
70	8,750.011	4,375.023	1,750.058	875.116	583.508	437.733	292.016	219.216	175.583	146.533	125.816
100	12,500.016	6,250.033	2,500.083	1,250.166	833.583	625.333	417.166	313.166	250.833	209.333	179.738
120	15,000.020	7,500.040	3,000.100	1,500.200	1,000.300	750.400	500.600	375.800	301.000	251.200	215.685
140	17,500.023	8,750.046	3,500.116	1,750.233	1,167.016	875.466	584.033	438.433	351.166	293.066	251.633
150	18,750.025	9,375.050	3,750.125	1,875.250	1,250.375	938.000	625.750	469.750	376.250	314.000	269.607
170	21,250.028	10,625.056	4,250.141	2,125.283	1,417.091	1,063.066	709.183	532.383	426.416	355.866	305.554
200	25,000.033	12,500.066	5,000.166	2,500.333	1,667.166	1,250.666	834.333	626.333	501.666	418.666	359.476

Deflection in decimal part of span

Span in ft.	0.080	0.085	0.090	0.095	0.100	0.110	0.120	0.130	0.140	0.150	0.160	0.170	0.180	0.190	0.200
	Multiplier														
10	15.758	14.847	14.038	13.316	12.666	11.546	10.616	9.832	9.161	8.583	8.079	7.636	7.244	6.895	6.583
20	31.516	29.695	28.077	26.632	25.333	23.093	21.233	19.664	18.323	17.166	16.158	15.272	14.488	13.791	13.166
40	63.033	59.390	56.155	53.264	50.666	46.187	42.466	39.328	36.647	34.333	32.316	30.545	28.977	27.582	26.333
50	78.791	74.237	70.194	66.581	63.333	57.734	53.083	49.160	45.809	42.916	40.395	38.181	36.222	34.478	32.916
70	110.308	103.932	98.272	93.213	88.666	80.828	74.316	68.824	64.133	60.083	56.554	53.453	50.711	48.269	46.083
100	157.583	148.475	140.388	133.162	126.666	115.469	106.166	98.320	91.619	85.833	80.791	76.362	72.444	68.956	65.833
120	189.100	178.170	168.466	159.794	152.000	138.563	127.400	117.984	109.942	103.000	96.950	91.635	86.933	82.747	79.000
140	220.616	207.865	196.544	186.427	177.333	161.657	148.633	137.648	128.266	120.166	113.108	106.907	101.422	96.538	92.166
150	236.375	222.713	210.583	199.743	190.000	173.204	159.250	147.480	137.428	128.750	121.187	114.544	108.666	103.434	98.750
170	267.891	252.408	238.661	226.375	215.333	196.298	180.483	167.144	155.752	145.916	137.345	129.816	123.155	117.225	111.916
200	315.166	296.950	280.777	266.324	253.333	230.939	212.333	196.641	183.238	171.666	161.583	152.725	144.888	137.912	131.666

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106. Total lengths of wires in spans

Deflection in decimal parts of span

Span in ft.	0.010	0.015	0.020	0.025	0.030	0.035	0.040	0.045	0.050	0.055	0.060	0.070	0.080
	Length of wire												
10	10.002	10.006	10.010	10.016	10.024	10.032	10.042	10.054	10.066	10.080	10.096	10.130	10.170
20	20.005	20.012	20.021	20.033	20.048	20.065	20.085	20.108	20.133	20.161	20.192	20.261	20.341
40	40.010	40.024	40.042	40.066	40.096	40.130	40.170	40.216	40.266	40.322	40.384	40.522	40.682
50	50.013	50.030	50.053	50.083	50.120	50.163	50.213	50.270	50.333	50.403	50.480	50.653	50.853
70	70.018	70.042	70.074	70.116	70.168	70.228	70.298	70.378	70.466	70.564	70.672	70.914	71.194
100	100.026	100.060	100.106	100.166	100.240	100.326	100.426	100.540	100.666	100.806	100.960	101.306	101.706
120	120.032	120.072	120.128	120.200	120.288	120.392	120.512	120.648	120.800	120.968	121.152	121.568	122.048
140	140.037	140.084	140.149	140.233	140.336	140.457	140.597	140.756	140.933	141.129	141.344	141.829	142.389
150	150.040	150.090	150.160	150.250	150.360	150.490	150.640	150.810	151.000	151.210	151.440	151.960	152.560
170	170.045	170.102	170.181	170.283	170.408	170.555	170.725	170.918	171.133	171.371	171.632	172.221	172.901
200	200.053	200.120	200.213	200.333	200.480	200.653	200.853	201.080	201.333	201.613	201.920	202.613	203.413

Deflection in decimal part of span

Span in ft.	0.090	0.100	0.110	0.120	0.130	0.140	0.150	0.160	0.170	0.180	0.190	0.200
	Length of wire											
10	10.216	10.266	10.322	10.384	10.450	10.522	10.6	10.682	10.770	10.864	10.962	11.066
20	20.432	20.533	20.645	20.768	20.901	21.045	21.2	21.365	21.541	21.728	21.925	22.133
40	40.864	41.066	41.290	41.536	41.802	42.090	42.4	42.730	43.082	43.456	43.850	44.266
50	51.080	51.333	51.613	51.920	52.253	52.613	53.0	53.413	53.853	54.320	54.813	55.333
70	71.512	71.866	72.258	72.688	73.154	73.658	74.2	74.778	75.394	76.048	76.738	77.466
100	102.160	102.666	103.226	103.840	104.506	105.226	106.0	106.826	107.706	108.640	109.626	110.666
120	122.592	123.200	123.872	124.608	125.408	126.272	127.2	128.192	129.248	130.368	131.552	132.800
140	143.024	143.733	144.517	145.376	146.309	147.317	148.4	149.557	150.789	152.096	153.477	154.933
150	153.240	154.000	154.840	155.760	156.760	157.840	159.0	160.240	161.560	162.960	164.440	166.000
170	173.672	174.533	175.485	176.528	177.661	178.885	180.2	181.605	183.101	184.688	186.365	188.133
200	204.320	205.333	206.453	207.680	209.013	210.453	212.0	213.653	215.413	217.280	219.253	221.333

RULE.—To find stress in lb. on wire of given span and deflection, multiply number in column answering to span and deflection by the weight per ft. of wire.

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107. Calculation of horizontal stress.* The foregoing tables give the factors by which the weight per ft. of conductor may be multiplied, in order to determine the horizontal stress in the span. Values are given up to 200 ft. (61 m.) spans, and to 20 per cent. deflections. For any span greater than 200 ft. (61 m.) the table may still be used, if it be remembered that for a given percentage deflection, the stress is proportional to the span. Thus for a 1,500-ft. (457 m.) span having 2.0 per cent. deflection, and a total weight of 0.5 lb. per ft. (1.64 lb. per m.) the horizontal stress will be (from 150-ft. span)

$$t = 938 \times 10 \times 0.5 = 4690 \text{ lb.}$$

In the same way, the length of this span wire (Par. **106**) will be (from 150-ft. span)

$$l = 150.16 \times 10 = 1501.6 \text{ ft.}$$

The tables were computed from formulæ given in Weisbach's "Mechanics of Engineering," page 297 (seventh American edition, translated by Eckley B. Cox, A.M.)

$S \times W$ = horizontal stress in wire at centre of span (lb.) (41)

$$S = y^2/2x + x/6 \text{ (ft.)} \quad (42)$$

$$l = y[1 + (2/3)\ (x/y)^2] \text{ (ft.)} \quad (43)$$

$$x = 3S - \sqrt{9S^2 - 3y^2} \text{ (ft.)} \quad (44)$$

$$y = \sqrt{(3yl - 3y^2)/2} \text{ (ft.)} \quad (45)$$

where y = one-half the span, l = one-half the length of the span wire, x = deflection at centre in same units as y, and w = dead weight per ft. of wire.

108. Temperature variations will change the length of the span, and as the sag and tension are very sensitive to changes in the length of span, the effect of change of temperature must be considered. With a change of tension, the length of the wire will be changed, due to stretching or contracting. As stretch and temperature change are interrelated and occur simultaneously, their combined effect must be determined. As an analytical calculation is difficult to make, the solution is better determined by graphical methods. For every degree fahr. change in temperature, the length of unstressed copper will change 0.00096 per cent., and of aluminum 0.00128 per cent.

109. †Properties of conductor materials

Copper	Ultimate strength per sq. in.	Elastic limit	Mod. elasticity, E	Coef. expansion, θ
Solid, soft-drawn.	32–34,000	28,000	12,000,000	0.0000096
Solid, hard-drawn.	50–55–57–60,000	30–32–34–35,000	16,000,000	0.0000096
Stranded, soft-drawn.	34,000	28,000	12,000,000	0.0000096
Stranded, hard-drawn.	60,000	35,000	16,000,000	0.0000096
Aluminum Stranded.....	23–24,000	14,000	9,000,000	0.0000128

(See Sec. 4 for detailed data on Conductors)

110. The maximum stress in a span occurs when it has its greatest loading of ice or sleet, minimum temperature, and maximum wind velocity blowing at right angles to the line. The loading usually assumed is 0.5-in. layer of ice at −20 deg. fahr. (−29 deg. cent.) and a wind pressure of 8 lb. per sq. ft. (at a velocity of about 57 miles per hr.) The load under these conditions may then be determined from Par. **104**, and the stress from Par. **105**, or calculated from Eq. 36, Par. **103**.

The heaviest loading recommended by the "National Electrical Safety Code" (third edition, 1920) is ½ inch of ice and zero deg. fahr. It is doubtful however, if these conditions give sufficient factor of safety for those regions where weather conditions are unusually severe.

111. Example of stress-sag calculation. Problem: Required to find the proper sag for a 600-ft. span of No. 0000 hard-drawn solid copper, at

* From "Wire in Electrical Construction" by John A. Roebling's Sons Co.

† Report of the Joint Committee on Overhead Construction, N. E. L. A. May, 1911, Vol. II, page 374.

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maximum (summer), minimum (winter-loaded), and stringing (unloaded) temperatures.

From Par. **104**, for 0.5-in. ice, and 8 lb. per sq. ft. wind pressure, the total load per lin. ft., w, is 1.575 lb. The allowable tension, t, is 4,150 lb. (corresponding to 25,000 lb. per sq.in.). The sag may be calculated from Eq. 37, Par. **103**. $d = [(600)^2 \times 1.575]/(8 \times 4{,}150) = 17.08$ ft. at the assumed minimum temperature. This is the sag under ice load at -20 deg. fahr.

The maximum sag will occur at $+120$ deg. fahr., the assumed maximum temperature, with no load other than the conductor itself and no wind.

To determine this sag, first consider that all the stress is removed from the conductor, and determine its length under this condition.

The change of length due to removing the load, $\Delta l = tl/EA$. (46)

In this expression, t is the tension in lb., l, the length in ft., E, the modulus of elasticity, in lb., A, the cross-section of the conductor, in sq. in. Values of EA are given in Par. **104**.

The original length, from Eq. 38, Par. **103**, is $l_1 = 600 + [8 \times (17.08)^2/(3 \times 600)] = 601.297$ ft. $\Delta l = 4{,}150 \times 601.297/2{,}659{,}000 = 0.939$ ft. The span, then, if all stress were removed, would have the hypothetical length at -20 deg. fahr., $601.297 - 0.939 = 600.358$ ft. This often results in a value less than the span length. At zero deg. fahr., the length would be given by

$$l = l_0(1 + \alpha t;) \quad (47)$$

Where l_0 is the length at zero deg. fahr., α is the coefficient of expansion, t is the temperature in deg. fahr., $l_0 = 600.358/[1 + 0.0000096 \times (-20)] = 600.473$ ft., $d_0 = \sqrt{[3 \times 600(600.473 - 600)]/8} = 10.31$ ft. (Eq. 38, Par. **103**.)

112. To obtain the sag at zero deg. fahr., no ice and no wind load, the stress-sag curve ab should first be plotted (Fig. 47), having $w = 0.641$ lb. per ft., weight of conductor with load removed (Par. **104**). The table of Par. **105** is very convenient for this purpose.

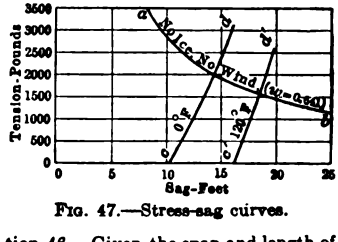


FIG. 47.—Stress-sag curves.

Curve ab shows merely the *tension* in the unloaded conductor for different *sags*. The problem is to find the sag and tension at some particular *temperature*, which point must lie on curve ab. For a given temperature, by Hooke's Law, the length of span changes with the tension. Assuming different values of tension, different lengths of span are found by equation 46. Given the span and length of conductor just found, the sag can be determined, using eq. 38, Par. **103**. This sag is plotted against tension which gives curve cd; where this curve intersects the sag-tension curve ab will be the sag at zero deg. fahr., when the conductor has no load other than its own weight.

Thus, at a tension of 3,000 lb.,
$l_1 = 600.473 + [(600.473 \times 3{,}000)/2{,}659{,}000]$
$= 600.473 + 0.678 = 601.151$ ft. (from Eq. 46).
$d = \sqrt{[1{,}800(601.151 - 600)]/8} = 16.09$ ft. (from Eq. 38, Par. **103**). From the intersections, sag at zero deg. fahr. = 14.4 ft. and tension at zero deg. fahr. = 2,000 lb.

113. The sag at another temperature may be found by increasing the asbcissas by a distance, determined from Eq. 47 and Eq. 38, Par. **103**. Thus, to find the sag and tension for 120 deg. fahr., $l = 600.473\,(1 + 0.0000096 \times 120) = 601.163$ ft. at 120 deg. fahr. and zero stress; $d = 16.18$ ft.

The sag and stress should then be computed as in Par. **112**, and a new stretch line $c'd'$ plotted. The maximum sag (assumed at 120 deg. fahr.) occurs where $c'd'$ cuts ab. It is equal to 18.5 ft., and the corresponding tension is 1,560 lb.

114. Data used when stringing. A set of stretch curves similar to those of Fig. 47 for several temperatures should be furnished the foreman in charge of stringing the wire, in order that he may adjust the sag, or tension (by means of a dynamometer) to its proper value for the temperature at the time of stringing. It must be remembered that the temperature of the

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wire, when the sun is shining, may be several degrees higher than that of the surrounding air.

115. With the supports at different levels, the line forms a catenary, the lowest point of which is no longer midway between supports. The curve can, however, be prolonged until it reaches a point which is at the same level as the higher support (Fig. 48) and the distance x_1 to the lowest point of the catenary will be equal to half the assumed span, S', and may be computed.

$$x_1 = \frac{S}{2} + \frac{ht}{wS} \quad \text{(ft.)} \qquad (48)$$

$$x_1 = S \frac{\sqrt{d}}{\sqrt{d-h}+\sqrt{d}} \quad \text{(ft.)} \qquad (49)$$

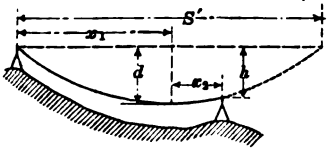


FIG. 48.—Supports at different levels.

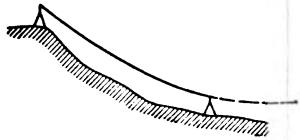


FIG. 49.—Condition for upward pull at lower support.

where S is the horizontal distance between supports, d the sag measured from the higher support, t the tension in the wire in lb. at the higher support, w the weight in lb. per unit length, h the difference in height of supports, all distances expressed in feet.

Eq. 48 is useful when the span and the allowable stress are given; and Eq. 49 when the span and sag are given. Eq. 48 is correct to within 2 to 4 per cent. when neither the sag nor difference in height of supports exceeds 15 per cent. of the span. Eq. 49 has an error of less than 1 per cent. under these conditions.

The sag d may be computed,

$$d = d'\left(1 + \frac{h}{4d'}\right)^2 \quad \text{(ft.)} \qquad (50)$$

where d' is the sag as determined by Eq. 37, Par. **103**, for the same span, S, and the same loading.

Also

$$x_2 = \frac{S}{2}\left(1 - \frac{h}{4d'}\right) \quad \text{(ft.)} \qquad (51)$$

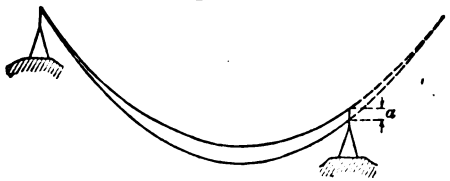


FIG. 50.—Error introduced by assuming constant equivalent span.

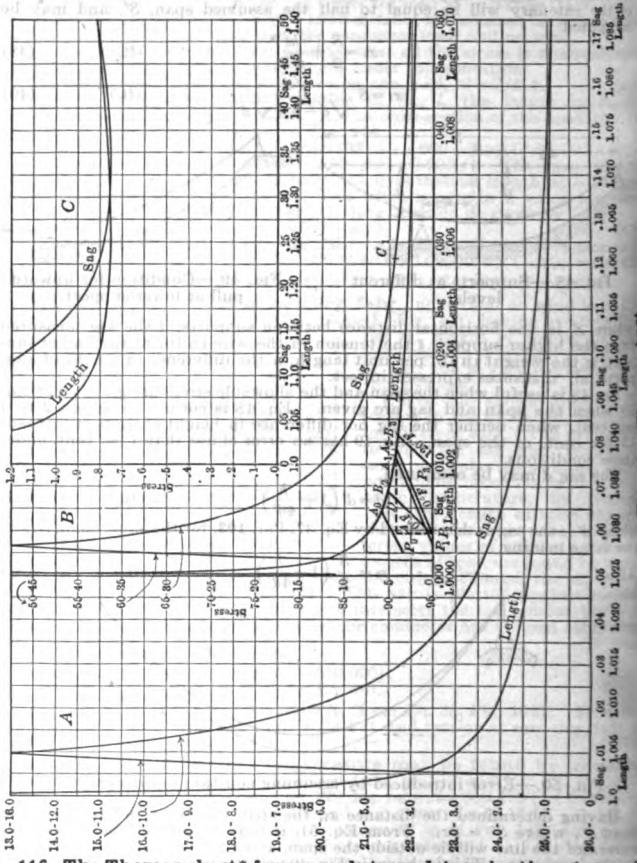
Having determined the distance x_1, the span may then be treated like a span S', where $S' = 2x_1$. From Eq. 51, if $h/4d'$ is greater than unity, the vertex of the line will lie outside the span, and there will be an upward pull on the insulator. This is shown in Fig. 49 and the span should be so designed that this condition does not occur.

Load and temperature changes may be computed as in Par. **112** and **113**, but a certain error is introduced in assuming that the length of equivalent

*Thomas, Percy H. "Sag Calculations for Suspended Wires." *Trans.* A. I. E. E., Vol. XXX (1911), p. 2229.

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span remains unchanged. Except for accurate work, this error is negligible. The error increases or decreases with the difference in height of supports by an amount, a, Fig. 50. For accurate work, however, the length of line in the span may be computed from Eq. 38 knowing x_1, x_2 and d (Fig. 48), and the effects of changes of load and of temperature may also be computed. The new distance x_2 is determined and the new equivalent length of span found.



116. The Thomas chart* for sag and stress determinations is based on the following: Imagine a given span to be reduced to a length of 1 ft. without changing the shape of the curve. The percentage sag will remain the same

* Thomas, Percy H. "Sag Calculations for Suspended Wires." *Trans.* A. I. E. E., Vol. XXX (1911), p. 2229; Chart, Supplement. *Elec. World* Nov. 16, 1912.

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but the sag, stress and length of wire will be reduced in direct proportion. The stress for a definite sag is proportional to the weight per unit length of the wire, including ice and wind loads. The curves, Fig. 51, show the relation between sag, length of wire and stress, for a 1-ft. span loaded uniformly with 1 lb., and are based on the equation of the catenary. Three sets of curves, *A*, *B*, and *C*, are given, all plotted to different scales. Curve *A* is good for sags from 2 to 15 per cent.; curve *B*, for sags less than 2 per cent.; curve *C*, for very large sags, being especially useful for spans on steeply inclined slopes. The chart in Fig. 51 is too small for accurate work, but the data from which the curves were plotted may be obtained from the original paper.

117. Use of the Thomas chart. By means of these curves, the sag, stress, and length of any span may be easily determined. Divide the allowable stress in the wire by the span and weight per unit length.

$$t = \frac{T}{w \times S} \quad \text{(lb.)} \qquad (52)$$

where t is the tension in lb. in a 1-ft. span; T the allowable tension in lb. in the actual span; w the weight in lb. per ft. (wire, ice and wind); S the distance in ft. between supports.

From the chart, determine the length and sag corresponding to t, as A_1 and C_1 (Fig. 51). Then the sag and length in the actual span will be the values just obtained multiplied by the actual span in ft. If the sag, or length, be given, the other quantities may be found by reversing the process.

With supports at different levels, the span may be computed as outlined in Par. **115**, and the chart then used for the total equivalent span.

118. The effect of temperature may be determined with the Thomas chart by finding the length of wire, with all stress removed, from Eq. 46, Par. **111**, using the stress in the *actual* span, and marking this point on the chart for the one-foot span (as P_1, Fig. 51). The elongation of the wire is proportional to the stress, so the straight line P_1A_1 will be the stress-length or "stretch" line for this load and temperature. If the sag is small, P_1 may be less than unity, but the line may be drawn by determining some other point P_2 (Eq. 46), and drawing P_2A_2. To determine the sag and stress at any temperature, determine the length of the unstressed wire at zero deg. fahr. (−17.8 deg. cent.) by Eq. 47, Par. **111**, as at P_2. For the same loading, the stress-length line at zero deg. fahr., P_2A_2, will be parallel to P_1A_1 and A_2 is the length at zero deg. fahr. of the 1-ft. span. Let this be l_1, and the corresponding stress and sag be t_1 and d_1 respectively. The values in the actual span may then be found.

$$\text{Actual length} = Sl_1 \qquad (53)$$
$$\text{Actual stress} = St_1w \qquad (54)$$
$$\text{Actual sag} = Sd_1 \qquad (55)$$

where S is the actual span in ft., and w the load in lb. per ft. of line.

The length axis may then be marked off in divisions proportional to temperatures, and parallel lines drawn, from which the lengths, stresses and sags may be determined.

119. The effect of ice and wind is determined by use of the Thomas chart as follows: Suppose the values in Par. **118** to be computed for maximum loading (ice and wind). When these loads are removed, the weight per ft. is reduced to w_o (the weight per ft. of the wire and the stretch in the wire will be $\frac{w_o}{w}$ of what it was before, for a given alone stress in the 1-ft. span. Therefore, along the line $A\ A_2$ make $AD/AA_2 = \frac{w_o}{w}$ and draw P_2B_2 through D. The intersection of this line with the length curve will give the results as obtained in Par. **118**, substituting w_o for w. The temperature lines may be found as before, P_2B_2 being drawn at 120 deg. fahr. (49 deg. cent.) and parallel to P_2B_2.

120. Example of calculation, using Thomas chart. Consider the problem of Par. **111**, where $S = 600$ ft., $w = 1.575$ lb., $T = 4{,}150$ lb.

S is the distance between supports; w is the weight (including wire, ice, and wind) per unit length; T is the allowable tension.

The tension in a 1-ft. span, having a 1-lb. load, will be $t = 4{,}150/(1.575 \times 600) = 4.395$.

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From curve B, the sag will be 0.0286 ft. (C_1) and the length 1.00215 ft. (A_1). The true sag and length will be $Sd_1 = 600 \times 0.0286 = 17.16$ ft. $Sl_1 = 600 \times 1.00215 = 601.290$ ft. The length, unstressed, may be found (Eq. 46, Par. 111).

$$\Delta l = (1.00215 \times 4{,}150)/2{,}659{,}000 = 0.00156 \text{ ft.}$$

$$l_1 = 1.00215 - 0.00156 = 1.00059 \text{ ft.}$$

A line P_1A_1 is drawn from P_1 (length = 1.00059) to A_1, the original point on the length curve. The length at zero deg. fahr. is found from Eq. 47, Par. 111. $l_0 = 1.00059/[1 + 0.0000096 \times (-20)] = 1.00078$ ft. A line P_2A_2 is drawn (where $P_2 = 1.00078$) parallel to P_1A_1. At zero deg. fahr., with wind and ice loads,

	Chart	Actual
Length	1.00224 ft.	$600 \times 1.00224 = 601.344$ ft.
Stress	4.2 lb.	$600 \times 4.2 \times 1.575 = 3{,}965$ lb.
Sag	0.0295 ft.	$600 \times 0.0295 = 17.70$ ft.

To find the length, stress and sag when the loads are removed. At zero deg. fahr., no ice, and no wind, $w_0 = 0.641$ lb. At the stress as now shown on the chart of 4.2 lb., the stretch will be $(1.00224 - 1.00078)0.641/1.575 = 0.00059$, and the length $1.00078 + 0.00059 = 1.00137$. Draw P_2B_2 through 1.00137 at the 4.2 lb. ordinate (at D). Graphically

$$AD/AA_2 = 0.641/1.575$$

Then, at zero deg. fahr., no ice or wind,

	Chart	Actual
Length	1.0015 ft.	$600 \times 1.0015 = 600.90$ ft.
Stress	5.1 lb.	$600 \times 5.1 \times 0.641 = 1{,}960$ lb.
Sag	0.0244 ft.	$600 \times 0.0244 = 14.6$ ft.

The unstressed length at 120 deg. fahr. is found from Eq. 47, Par. 111. $1.00078(1 + 120 \times 0.0000096) = 1.00193$ ft. At $P_3(l = 1.00193)$ draw P_3B_3 parallel to P_2B_2. Then, at 120 deg. fahr.,

	Chart	Actual
Length	1.00234 ft.	601.40 ft.
Stress	4.1 lb.	1,577 lb.
Sag	0.031	18.6 ft.

These results check very closely with those already obtained using Fig. 47. The differences are due to errors in reading the charts, and to the assumption of a parabola rather than a catenary.

The distance P_1P_3 may be subdivided proportional to temperatures, and results may be found by drawing stretch lines parallel to P_2B_2.

121. The horizontal stresses in adjacent spans should be equal to minimize the longitudinal pull on the support. In level country and with equal spans, this may be easily accomplished by making equal sags at a given temperature. Unequal spans can be equalized only at one temperature, which should be the average temperature. Suspension insulators, by deflecting, tend to equalize unbalanced stresses. With pin-type insulators on rigid supports, the insulator is subjected to an unbalanced stress, and a slight deflection results. This changes the lengths of the spans slightly and consequently the sags, tensions, etc. The deflection tends to equalize the stresses in the two spans on either side of the insulator. The resulting sags, tensions, etc. can be computed with the equations which have been given. For equal horizontal stresses with the supports at different levels the wire in each span should form a portion of equal catenaries (parabola assumed) as shown in Fig. 52. This condition holds for but one temperature



FIG. 52.—Balanced horizontal stresses.

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122. Short-circuit due to unbalanced ice loads.* Ice loads on wires may drop from all but one span. If suspension insulators are used and the lines are arranged in a vertical plane, this span, aided by the longitudinal deflection of the suspension insulators, will sag heavily and the adjacent spans will be drawn up, as shown in Fig. 53. The phase wires may readily approach within easy arcing distance of one another and all three conductors, even, may touch, thus, causing a short-circuit. Also, if one wire alone loses its ice load, its whipping up may cause short circuit. This may be partially overcome by the use of shorter spans, more anchor towers, or better, by offsetting the middle conductor, thus making an isosceles triangle arrangement (see Fig. 67, isosceles triangle).

STRENGTH OF SUPPORTING MEMBERS

123. Insulators and pins must be designed to withstand the weight of conductor and any ice, sleet or snow load; the wind pressure acting on the conductor, and any other transverse force produced by a change in direction of the line; the longitudinal force due to unbalanced horizontal stresses in adjacent spans; the longitudinal stress occasioned by the breaking of a line conductor. It is desirable that they withstand a stress equal to the elastic limit of the conductor, when exerted in any direction in a plane perpendicular to the axis of the pin.

124. The cross arms must be designed to withstand the resultant of the forces of Par. **123**, and the dead weight of insulators and attachment. In addition, the cross arms must be secured to the pole so that they will not be wrenched loose by the turning moment which follows the breaking of one or more conductors on the same side of the pole. The results of "Strength Tests of Cross Arms," made by T. R. C. Wilson, are published in U. S. Government Forest Service Circular 204.

125. The supporting structure may be considered first as being a simple column and therefore must be designed to bear the compressive stress, due to its own weight and that of conductors, loads, insulators, cross arms and attachments. Also it may be considered as a cantilever and as such must be designed to withstand the shear and bending moments due to the transverse forces of the wind on conductors and supporting structure and also those occasioned by change in direction of the line; the longitudinal stresses due to unbalanced horizontal stresses in adjacent spans; stresses caused by the breaking of one or more conductors. In addition, the structure should be able to withstand the torsional stresses which result from the breaking of conductors on one side of the structure.

Wooden, steel, or concrete poles, designed to withstand the moments due to the horizontal forces, will have the necessary compressive strength, to bear the vertical loads. With towers of the light wind-mill type, this matter should be carefully considered. Where extreme rigidity at small expense is desired, the structure must be made of many light members, resulting in a more complicated tower, and a shorter life, due to the greater proportionate corrosion. A less rigid tower made of fewer but heavier members, will frequently answer the purpose, will be less expensive and of longer life.

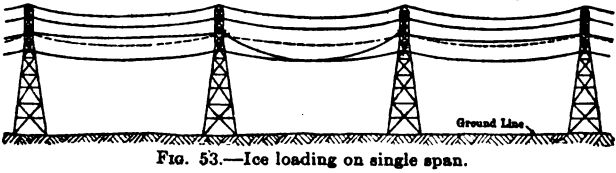


FIG. 53.—Ice loading on single span.

126. The transverse force due to the wind on the conductors should be assumed as 8 lb. per sq. ft.† of the projected conductor and ice area. A 0.5-in. (1.27 cm.) layer of ice is usually assumed. Values of the resulting pressure may be found in Par. **104.** The pressure on the pole or tower may be

*Greisser, V. H. "Effects of Ice Loading on Transmission Lines." *Trans.* A. I. E. E., Vol. XXXII (1913), p. 1829.

† Report of the Joint Committee on Overhead Line Construction, N. E. L. A May, 1911, Vol. II, p. 374.

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assumed to be 13 lb. per sq. ft. on one and one-half times the projected area of latticed structures. (Also see Sec. 12, Par. **166.**) The overturning moment may be greater without the ice load. Both conditions should be calculated. The stress due to an angle in the line may be readily computed by a simple resolution of the maximum stresses already calculated for the spans. The longitudinal forces, due to unbalanced horizontal stresses in adjacent spans, should be small in a well designed line, and may be determined if the stresses in each span at different temperatures are known. There is some question as to how many conductors may be assumed to be broken at one time. If a line is carefully strung, with no kinks or abrasions in the wires, and if the ends of the insulator clamps are well rounded, there is small chance of a line conductor breaking under ordinary load conditions. As an extra precaution, however, anchor towers are used at frequent intervals, and are so designed as to safely withstand the simultaneous breaking of several conductors. Where suspension insulators are used, the insulator string is thrown in the unbroken side of the span, and the increased sag decreases the ultimate pull. The force due to the jerk at the time of breaking is quite severe, and no reduction in the allowable stress should be made even if suspension insulators be used. The line structures should have a factor of safety of from 2 to 4, according to the importance of the line, the assumptions made in the design, and the local conditions.

127. A wooden pole should be a cubic parabola, to use the material to the best advantage. As this would be impractical, a truncated cone, having the diameter of the top two-thirds of that of the bottom, is the best approximation. With this shape, the pole will break theoretically at the ground line.

The allowable horizontal pull, P, on the pole may be calculated

$$P = \frac{T}{n}\frac{\pi d_2^3}{32l} \quad \text{(lb.) for a round pole.} \tag{56}$$

$$P = \frac{T}{n}\frac{d_2^3}{6l} \quad \text{(lb.) for a square pole.} \tag{57}$$

assuming that d_2, the ground diameter in inches, is one and one-half times the top diameter. In these formulas n is the factor of safety, l the length of the pole in inches, and T the tensile strength or modulus of rupture of the pole material, values of which are given in Sec. 12, Par. **164.** The factor of safety should be at least 5 or 6 for wood.

128. The stresses in steel poles cannot readily be calculated, due to the complications introduced by lattice work, cross bracing, etc., and the engineer is more or less dependent upon actual tests and manufacturers' guarantees for data relative to the load that a given structure may be expected to carry safely. Steel poles, for the same weight and material, have much less torsional strength than steel towers. Although they may be satisfactory under normal conditions of balanced load, their factor of safety may be much reduced if one or more wires on the same side of the pole should break.

129. The stresses in concrete poles may be computed approximately, knowing the moment of inertia of the top and bottom sections, the cross-section and tensile strength of the reinforcing steel, and the compressive strength of the concrete. Up to the present time, however, very little has been done along this line, and purchasers and manufacturers have been dependent upon actual tests of full-sized poles. The usual mixture of Portland cement (1 : 2 : 4, cement, sand and gravel) has a compressive strength after 7 days of 900 lb.; after 1 month, 2,400 lb.; after 3 months, 3,100 lb.; after 6 months, 4,400 lb.; all in lb. per sq. in.

130. Stresses in guys and anchors may be readily computed if the magnitude, direction, and point of application of the resultant force acting on the pole are known. The position of the anchor is determined, and the stress in the guy and anchor can be calculated by the well-known laws governing the composition and resolution of forces. The table in Par. **164** gives the diameters, strengths and weights of 7-strand galvanized steel wire such as would be used for guys (also see Sec. 4). When guys are used with wood or other poles, or towers capable of considerable deflection before failure, they shall be able to support the entire stress in the direction in which they act, the pole serving simply as a strut. The guy should be attached to the structure as near as practicable to the center of the conductor load to be sustained. Anchor rods shall be so installed as to be in line with the pull of the attached guy when under load, except in rock or concrete.

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131. The stress in towers may be computed by the well-known laws of statics, provided the tower is statically determined. Towers are usually constructed of four main angle members, cross-latticed and braced the entire length of the tower. These members must not only withstand the total compressive load of a simple column, but the members on either side of the tower may be subjected to additional compression due to the fact that the tower is also a cantilever. As steel fails in compression, the strength of unsupported compression members should be carefully checked, using well known column formulas. The following formula for *ultimate strength*, T, (lbs. per sq. in.) is commonly used.

$$T = \frac{40{,}000}{1 + \frac{1}{16{,}000} \cdot \frac{l^2}{r^2}} \qquad (58)$$

where l is the length of unsupported column member and r is the least radius of gyration of the column cross-section. A factor of safety of 2 or 2.5 is customary.

R. D. Coombs* shows, in the following table, that by using a different angle iron of less cross-sectional area, the strength of the main compression members is nearly doubled. Because of corrosion, this should not be carried too far, if a reasonable life is expected. It is generally conceded that $\frac{1}{4}$ in. for the legs and $\frac{1}{16}$ in. for the secondary members should be the minimum thicknesses of metal.

Section	Area, sq. in.	Length, ft.	l/r	Breaking strength, lb./sq. in.	Total breaking strength, lb.
4 in. by 4 in. by $\frac{1}{4}$ in. angle.	5.44	13	202	12,000	65,200
5 in. by 5 in. by $\frac{1}{16}$ in. angle.	5.31	13	159	16,000	85,000
6 in. by 6 in. by $\frac{1}{16}$ in. angle.	5.06	13	131	20,000	101,200

Except in very short members, angle lacing (and bracing) is preferable to flat lacing (and bracing), as angle members are stiffer and better able to resist tension and compression than are flat bars. Also, if the flat bars are slightly bent on handling, they are practically worthless as compression members.

As transmission towers are usually assembled on the field, bolts are used in the joints rather than rivets. About 12,000 lbs. per sq. in. can be used as the working shearing stress for such bolts. A bolted joint is much less efficient than a riveted one, as the friction between adjacent surfaces cannot be depended upon for holding. With time, the tower vibration due to wind often causes the nuts to work loose. Therefore, during erection the nuts should be gone over carefully, tightened, and the threads upset.

The calculation of the forces in the tower members due to torsion, particularly if the tower faces are battered, is difficult. Towers which are carefully designed rarely fail from such torsional forces alone. When designing a tower, it is not sufficient to use merely the assumed steady horizontal forces, but allowance must be made for the forces caused by the sudden jerk when a conductor breaks, particularly if the suspension string is thrown into the unbroken line.

132. The stresses in tower foundations are produced by the vertical loads V V, Fig. 54, due to the dead weight of the tower and its column loading. These forces must be opposed by the vertical resistances $V'V'$, at the base of each of the foundation members. To obtain the requisite bearing area, a flat grill work is usually riveted to the foot of the foundation, unless a concrete foundation is used. (See Fig. 60.) The horizontal force H, resulting from wind, unbalanced span tension, etc., produces a couple HX which must be resisted by a couple BY at the foundation. The couple HX increases the vertical load on the foundation members which are on the compression side and tends to produce an uplift in the anchor on the other

* Letter to *Elect. World*, Vol. LXII (1913), p. 544.

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side. This uplift is resisted by the weight of earth above the grill work. It is usually assumed that this weight is that of the earth included within a cone whose sides make an angle of 30 deg. with the vertical. The weight of earth is usually taken as 100 lbs. per cubic foot. A frequent cause of towers overturning is the lack of holding power in the freshly-tamped earth, and the softening of the earth resulting from rains, floods, etc.

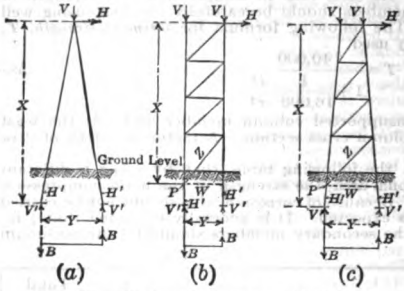
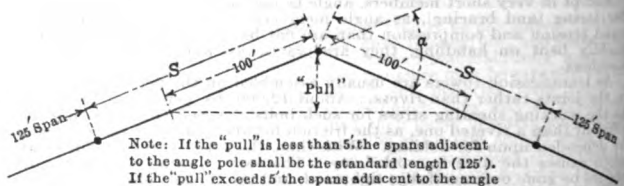


FIG. 54.—Stresses in towers, unbalanced spans, etc.

The entire shear produced by H must be transmitted to the foundation, and be resisted in the earth by horizontal resistances H', H'. Resistances H', H' are distributed forces and the point of application of their resultant is not known. Unless the relation between the magnitudes of the forces H', H' and their centers of application be known, or assumed, the tower is statically indeterminate. In the A frame (a), Fig. 54, the horizontal shear is entirely transmitted to the foundation through longitudinal stresses in the main angle members. Practical considerations, such as the attaching of cross-arms, usually preclude the use of straight A frames. In (b), practically all the shear must be transmitted through the member Z to the foundation at point P, where the foundation is usually bolted to the tower. Unless the point P has some special support, serious transverse stresses are developed in the tower leg and in the foundation member and a tendency to buckle results. Towers, after having successfully passed tests on rigid foundations in the shop, often fail at the



Note: If the "pull" is less than 5, the spans adjacent to the angle pole shall be the standard length (125'). If the "pull" exceeds 5 the spans adjacent to the angle pole shall be reduced to the distance "S" given in table.

Angle α	"Pull" in Feet	Span S	No. of 6000 Lb. Side Guys		
			1 Arm 6 Wires	2 Arms 12 Wires	3 Arms 18 Wires
Less than 6°	Less than 5'	125'	None	None	None
6°-11°	5'-10'	115'	None	1	1
11°-15°	10'-13'	105'	1	1	1
15°-22°	13'-19'	95'	1	1	2
22°-30°	19'-26'	85'	1	1	2
Over-30°	Over-26'	75'	1	2	2

FIG. 55.—Location of side guys.

point P in the field. In the later designs this point is usually buried, and a channel attached to the joint (see Fig. 60), in order to transmit the shear, to which the dangerous stresses would be due, directly to the earth. Another horizontal member, W, shown dotted, would give additional support.

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133. Location of poles and side guys may be determined by use of the table given with Fig. 55. The term "pull" refers to the deviation of the line and is equal to the distance from the pole to the straight line joining points on the line 100 ft. each side of the pole.

134. Flexible towers are used with a view to decreasing the line cost. Their design is based on the fact that with equal spans and sags on both sides of the tower, the stresses in the direction of the line are balanced. The towers are not intended to carry longitudinal stresses, but are designed to withstand any transverse stresses that may occur. They are held in position by the conductors, if pin insulators are used. When suspension insulators are used, a heavy steel galvanized ground wire is necessary to keep the towers in position. If a conductor breaks, the tower will deflect until the increased sag in the conductors and ground wire on the other side of the pole compensates for the unbalanced forces due to breaking. The towers should be designed to deflect from 12 in. to 24 in. without being permanently deformed. The unbalanced pull will not only be taken up by the tower at which the break occurs, but will be gradually absorbed by the other structures in the line. If a tower is actually pulled over, it is not a very serious matter because of its low initial cost, and ease with which another may be erected. About every mile there should be an anchor tower. Methods of computing the deflections and stresses in flexible towers have been published (see Bibliography 45 and 47). Such towers should be designed to carry from $\frac{1}{10}$ to $\frac{1}{20}$ the load for rigid towers and with this load should not be stressed beyond the elastic limit. The two legs or main members are usually made of channels, whereas in anchor towers the legs are usually made of angles. (See Fig. 60.)

135. Anchor towers, when used in connection with flexible towers, should be designed to withstand the stress produced by the breaking of all the conductors on one side, even when the line is loaded under the most unfavorable conditions. Under these circumstances, there should be no yielding of the foundations, and the tower should not be stressed beyond the elastic limit. With a line constructed entirely of rigid towers, these conditions may be somewhat modified, as the intermediate towers themselves are designed to take care of one or two broken conductors.

FUNDAMENTAL CONSIDERATIONS OF LINE CONSTRUCTION

136. The line location should in general be direct. Detours are often necessary, to avoid sections subject to severe lightning, to avoid country that may be inaccessible, to avoid swamps or hills that will make the construction difficult and costly. It may be necessary to pass near towns or villages where connected load may be profitable. However, angles in the line should be avoided whenever possible, as the unbalanced horizontal stresses require a stronger and more costly tower than the ordinary straight line tower.

The most direct right of way cannot always be obtained at a reasonable figure. County plat maps or U. S. Topographical Survey maps should be carefully studied with special reference to the villages along the route, the proximity of roads, hence accessibility, and the topography that will permit standard structures and spans. When the location is roughly determined, a small surveying party should go over the route, make a profile, locate swamps, streams, railroads, other power, telephone or telegraph lines, and should note the character of ground and probable location of supports. Profiles should be made 100 ft. on each side of the centre line, as well as at the centre line, since a supporting structure might be advantageously located a short distance from the centre, if an abrupt change in profile made an increased height of structure necessary to secure the proper clearance.

137. A private right of way is necessary for most high-voltage transmission lines, as the risk to life and property from high voltages is too great to permit circuits to be carried along highways. The width should be so chosen that no tree or other object located outside the right of way can fall across lines. Where very tall trees do occur, they should be bought and removed. It is advantageous to secure the right of way near a highway, as the construction materials can be easily hauled to the tower locations. The line will also be more accessible for repairs, and patrolling is facilitated. Where the line must pass over private property, if possible it should follow the division lines.

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138. The proper form of contract should be executed,* when the consent of the proper parties is obtained. In many cases, as in sparsely settled districts, the land may be bought outright. The best practice, however, is to acquire perpetual right under easement, or for a term of years, with the right to renew the contract at the expiration of this time. Legal questions of importance should be settled by counsel.

139. The conductor material will usually be copper, aluminum, or steel-reinforced aluminum. The relative advantages and disadvantages of these are described in Par. **61** to **64** incl.

140. The spans for any line will usually vary in length. For level or undulating country, a standard span ranging from 100 to 800 ft. may be used. In hilly or broken country, the support must be erected at advantageous points regardless of the varied length of span that may result. With increased length of span, the number of structures and insulators (hence maintenance charges) is decreased, but the height of tower is increased. The cost of the tower may vary as the cube of the height. Other things being equal, the span should be so selected that the total line cost is a minimum. (See Par. **236.**)

141. Extra long spans must be anchored at each end. To secure sufficient tensile strength in the insulator, it is often necessary to connect a number of strings of suspension insulators in parallel. In order that each string may take its own share of the load, a *strain yoke* (Fig. 35) is used.

142. The conductor spacing should be such that the wires cannot swing within arcing distance of one another in the span. When suspension insulators are used, the wires at the insulators should not be able to swing within arcing distance of the pole or tower. Allow a 45-deg. deflection from the vertical for copper and 60-deg. deflection for aluminum under the worst conditions of loading. Assuming one of the phase conductors to hang vertical and the other to swing to the above angle, no two conductors must come within arcing distance of each other. Fig. 56 shows the usual spacings employed.

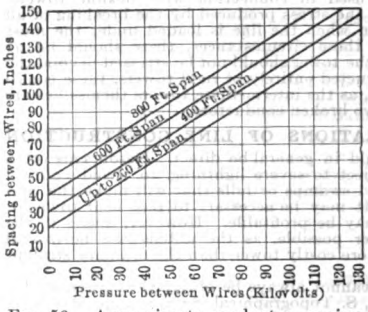


FIG. 56.—Approximate conductor spacing.

143. †Weighted conductors. Where small conductors are used with suspension insulators, it may be impracticable to increase the spacing by an amount sufficient to prevent the wires swinging more than 60 deg. By hanging a weight on the end of the insulator string, the maximum swing may be kept within this limit. Such weights tend to prevent the propagation of mechanical waves longitudinally.

144. The type of line construction should be decided upon after the location of the line has been determined. The choice lies between wooden poles, steel poles, concrete poles, rigid steel towers, and the flexible tower system.

When selecting the type of line, the locality through which the line passes, the initial cost, the reliability, the ultimate life, and the maintenance should all be carefully considered.

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*Croswell, S. G. "The Law Relating to Electricity."
Joyce, J. A. and H. C. "A Treatise of Electric Law."
Tiffany, H. T. "The Law of Real Property." Chap. 12 (Easements), Chap. 24 (Prescription for Incorporeal Things), Chap. 30 (Appropriation under Eminent Domain).

†Buck, H. W. "Practical Operation of Suspension Insulators." *Trans.* A. I. E. E., Vol. XXXIII (1914), p. 131.

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145. The poles or towers should be staked out by the surveying party; following should come a digging party provided with a steel or wooden template by which the corner holes may be located. This party should be followed by another to install the concrete foundations, if such are to be used, and then by the erecting gang.

POLES

146. Wooden poles, though apparently the cheapest form of construction, should seldom be used, except on short or relatively unimportant lines. The life of untreated poles (Par. **147**) ranges from 6 to 15 years, depending on the type of wood and the climatic conditions. When treated, their life may reach 20 years or more. Though wooden poles and cross arms give better insulation (per pole) to the system, they may be charred or badly burned by leakage currents or by conductors that fall from insulators. Although less likely to be struck by lightning, they are usually shattered or badly damaged when struck. The large number of poles required per unit length of line, decreases the (total) insulation of the system and increases the number of insulator troubles in direct proportion.

Wooden poles are still used to a considerable extent in transmission. Sixty per cent. of the wooden poles used in the United States are cedar and 20 per cent. are chestnut. On the western coast, redwood is used to a great extent; other woods, such as pine, cypress, juniper, Douglass fir, tamarack, and oak are occasionally used. Cedar, owing to its lightness and to its long life, which varies from 10 to 30 years depending on the climate and soil, is the most common pole timber, although the supply in the eastern states is practically exhausted. Chestnut, though heavy and not as long-lived as cedar, is used in the eastern and middle states. Redwood poles have a long life, and are usually sawed from large trees. Pine, though heavy in resinous products, rots very rapidly and does not last more than 4 or 5 years unless treated. Cypress stands very well in its native climate, but is short lived in the north. The other woods are used only occasionally, though the present methods of pole treatment will widely increase the timber available for poles.

147. Average life of untreated poles.

Cedar	15 years	Juniper	8.5 years
Chestnut	12 years	Pine	6.5 years
Cypress	9 years		

148. Preservative treatment of poles is attracting much attention among large users, as the available supply of timber is constantly decreasing and the price rising. Two preservatives are in general use: creosote and zinc chloride, though copper sulphate has also been used to some extent. Creosote, though expensive, is the most satisfactory preservative, as it does not contain water nor is it affected by water, and has valuable antiseptic properties. Zinc chloride is far cheaper, but as it is carried into the wood poles in a water solution, the water must be dried out again, and the pole will readily absorb moisture later.

149. Brush treatment of seasoned poles consists of two applications of hot creosote (220 deg. fahr.) about 24 hr. apart. The treatment should extend at least 2 ft. above the ground line, and the pole should be very dry at the time of application. This is the simplest form of treatment; it costs from 15 to 40 cents per pole, and increases the life 2 to 3 years.

150. In the open tank method of pole treatment the dry pole butts are placed in tanks containing hot creosote at 220 deg. fahr. (105 deg. cent.), for from 4 to 8 hr., and are then allowed to stand in a "cold" bath between 100 and 150 deg. fahr. (38 and 66 deg. cent.) from 2 to 4 hr. Where the top of the pole is subject to rot, as in the south, the whole pole may be treated by this process. The penetration is about three times as great as with the brush treatment. The estimated increase of life is 20 to 25 years.

151. In the full-cell (Bethel) process of pole treatment, the poles are placed in an iron cylinder, about 125 ft. long and 8 or 9 ft. in diameter. Live steam at 20 lb. pressure is admitted and maintained for several hours. The steam is then blown out of the cylinder, and pumps exhaust as much of the air as possible. At the end of the vacuum period, the preservative at about 150 deg. fahr. (66 deg. cent.) is admitted and is forced into the wood under pressure. This insures a deep penetration of the preservative and a

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long life to the pole. No data as to the life of such poles are available, but poles in England under similar treatment are still in service at the end of 60 years.

152. The burnettized creosoted butt process of pole preservation is similar to the full-cell method, except that zinc chloride is always used in the tank. The butt, to a foot or two above the ground line, is then impregnated to a slight depth with creosote under pressure. This prevents the zinc chloride from leeching out, and is much cheaper than a complete treatment of creosote.

153. Tabulation of pole cost, per-annum pole cost, and cost of butt treatment—western red cedar*

Based upon present market prices (Oct. 1, 1920) delivered Central States rate of freight

Size of pole	8 in./ 35 ft.	8 in./ 40 ft.	8 in./ 45 ft.	8 in./ 50 ft.	8 in./ 55 ft.	8 in./ 60 ft.
Price delivered, Central States	$17.75	$18.55	$27.15	$28.50	$34.50	$39.25
Cost in place, shaved but not painted or stepped, based on wholesale new construction	8.90	11.10	12.65	14.55	16.55	18.75
Total cost in line	$26.65	$29.65	$39.80	$43.05	$51.05	$58.00
Using average of 13½ years life; per annum cost	1.97	2.20	2.95	3.19	3.78	4.30
Cost of butt-treatment:						
Specification *A*	2.25	2.70	3.30	4.00	4.80	5.55
Specification *AA*	1.90	2.10	2.55	2.90	3.30	4.00
Specification *B*	3.45	4.00	4.35	4.80	6.00	7.20
Guaranteed penetration process	3.80	4.40	4.80	5.30	6.60	7.90
Added life necessary to pay entire cost of treatment:	Years	Years	Years	Years	Years	Years
Specification *A*	1.14	1.22	1.12	1.25	1.28	1.3
Specification *AA*	0.96	0.95	0.86	0.90	0.87	0.93
Specification *B*	1.75	1.81	1.47	1.50	1.58	1.67
Guaranteed penetration process	1.92	2.00	1.62	1.66	1.74	1.83

Specification *A* provides for a continuous submersion of that part of the pole to be treated, in high grade Carbolineum, for a minimum of fifteen minutes. Specification *AA* provides for a continuous submersion of that part of the pole to be treated, in high grade Creosote, for a minimum of fifteen minutes. Specification *B* provides for an alternately hot and cold submersion in Creosote for a minimum of six hours. The guaranteed penetration process quarantees one-half inch penetration in every portion of the pole in that area between the plane designated as the height of treatment to a plane one and one-half feet below the standard ground line, unless the sapwood is less than one-half inch in thickness, in which case the impregnation is to the full depth of the sapwood.

154. Char and tar the butts of poles before setting if they are not creosoted. This is done by placing the pole upon a skid over a slow fire, gradually revolving it until the butt to about 1 ft. above ground level is thoroughly charred. While hot, it is given two or three coats of tar with a stiff brush and is then set. This will increase its life perhaps a year.

155. Wooden pole specifications. Each pole should be of good quality of live growing timber, free from knots and shakes, and sound in all respects; the grain should be close and hard, with the annular rings closely pitched and

* Page & Hill, Minneapolis, Minn.

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with a sound heart. Each pole should be straight and well proportioned, free from all objectionable bends; should have the natural butt of the tree and should be squarely sawn, without trimming. Poles should vary in size by lengths of about 5 ft.; they should be cut between the first of November and the first of March, and after being felled they should be carefully trimmed, the bark removed and the butt squared. The poles should be piled with open spaces between, raised from the ground and allowed to season for at least a year or more. After seasoning, the top of each pole should be roofed and the suitable number of gains cut for the cross arms. The specifications vary with the kind of wood.

156. *Depth of wooden poles in the ground

Length over all (ft.)	Depth for straight line (ft.)	Depth, curves, corners and points of extra strain (ft.)	Length over all (ft.)	Depth for straight line (ft.)	Depth, curves, corners and points of extra strain (ft.)
30	5.0	6.0	60	7.0	7.5
35	5.5	6.0	65	7.5	8.0
40	6.0	6.5	70	7.5	8.0
45	6.5	7.0	75	8.0	8.5
50	6.5	7.0	80	8.0	8.5
55	7.0	7.5			

157. Wooden-pole settings. All holes should be dug large enough to admit the pole without forcing, and should have the same diameter at the top as at the bottom. The pole may be "piked" into position, but it is usually much cheaper to employ a gin wagon, and to use the team for raising the pole. Forty to fifty poles per day can be thus raised, with only two linemen and a teamster.

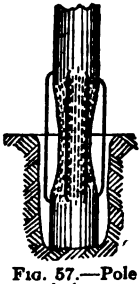


FIG. 57.—Pole repairing at ground line.

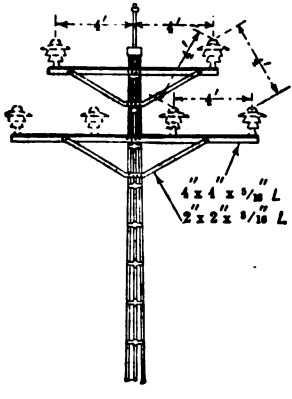


FIG. 58.—Tripartite steel pole.

158. Crib-bracing can be used, where the poles are set in loose, or marshy soils. For further discussion see Sec. 12, Par. 173.

159. The sand barrel is a useful expedient in digging holes or setting poles in sandy or loose soils. See Sec. 12, Par. 173.

160. A concrete foundation may be used for wooden poles where exceptional stability is desired. This concrete filling should extend at least a

* Report of Committee on Overhead Line Construction, N. E. L. A. May, 1911, Vol. II, p. 374.

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foot from the pole on all sides, should be carried above the ground line and bevelled to shed water, and should consist of one part Portland cement, three parts sand, and six parts broken stone or clean gravel, mixed wet. (See Fig. 47, Sec. 12.)

161. Special pole settings. In marshy ground, more elaborate devices, as shown in Fig. 47, Sec. 12, are often required for a satisfactory foundation.

162. Pole repairs. Wooden poles usually fail by decay at the ground line. If they are long enough, they may be sawed off and set again. A very satisfactory way of repairing such poles without disturbing them is to drive U-shaped rods in the poles at the ground line, as shown in Fig. 57, and fill the space with concrete. Poles reinforced in this way are said to be stronger than when new, and their life is greatly prolonged.

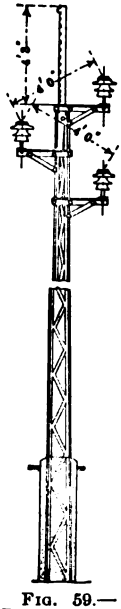


FIG. 59.—Bates expanded steel pole.

163. Steel poles cost but little more than wooden poles, when the erection and labor costs are considered, require no assembling at the point of erection, are not injured by fire, birds and insects, and are not damaged by lightning. Their field is the moderate line, with spans from 250 to 350 ft. in length, running along roadways or where space is limited. Their life is from 25 to 50 years, and even more depending upon their upkeep.

164. The tripartite steel pole, shown in Fig. 58, consists of three continuous U parts, held together by "spreaders" and "collars" bolted together. The strength and rigidity of the pole can be increased by increasing the number of these members, and the pole is everywhere accessible, so that it can be readily painted and inspected. Tripartite poles may be shipped either assembled or "knocked down," and are therefore well adapted to the lighter lines, particularly where transportation is difficult. They can be assembled by unskilled labor. In ordinary soil, and with a concrete foundation, it has been asserted that the poles need only be buried for one-tenth their length.

165. The Bates' expanded steel truss pole, Fig. 59, is made from rolled *H* sections. The web is sheared longitudinally by a rotary shear, leaving intact portions at fixed intervals throughout the length of the web. The intact portions are staggered. The section is heated to a cherry-red color and is then expanded by a special machine which grips the flanges through its entire length and expands the section to the desired dimension while hot. This creates a series of triangles in alignment, thus forming a one-piece steel truss. The manufacturers claim greater strength, lower cost and maintenance, and lighter weight than fabricated poles, or tubular poles. These poles may be used as members of *A* frames, anchor towers, special structures, etc. They are also well adapted for use as flexible towers in this type of transmission line design.

166. Steel poles should invariably have a concrete foundation, in order to obtain adequate bearing area. Steel-pole foundations are shown in Fig. 59.

167. Concrete poles are coming to be used for high-voltage transmission. Their maintenance is very low, they are not injured by the attacks of insects, fire, etc., and, apparently, are not damaged by lightning. They can be used in the most accessible places only, as they must be constructed, in most cases, when erected. Their weight results in high transportation costs. Though there are as yet no data regarding their life, it is probably long. Two poles, 150 ft. (45.8 m.) high, 11 in. (28.0 cm.) square at the 31 in. (78.7 cm.) square at the bottom, and capable of withstanding, without guys, a 2,000-lb. horizontal pull at the top, have been successfully installed by the Hamilton Power, Light and Traction Co., at the Welland Canal Crossing.

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STEEL TOWERS

168. Advantages. Steel towers in the open country, and for trunk lines of large capacity and long spans, are unquestionably the best type of construction. The two systems, the rigid and flexible, are both in general use, and the latter is becoming more used. The flexible system compares favorably even with wooden poles, as far as first cost is concerned, since

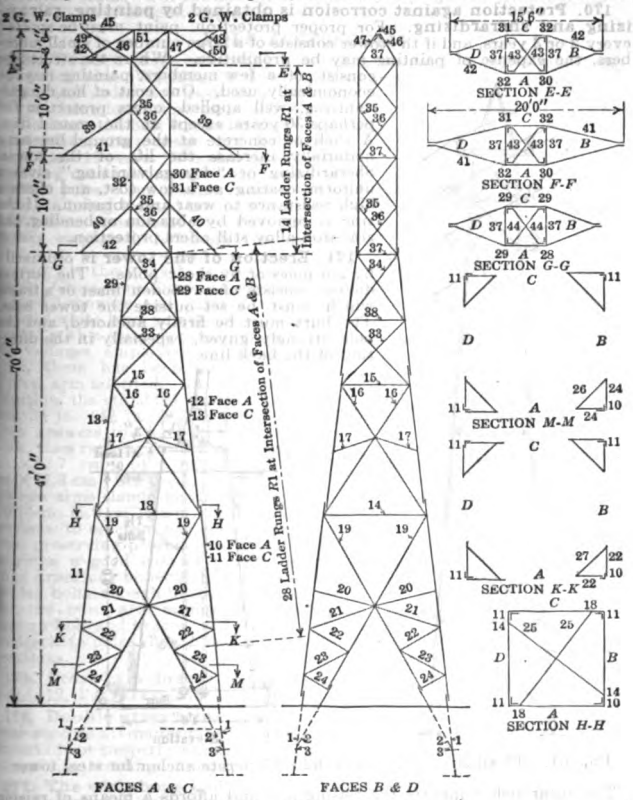


FIG. 60.—Rigid steel tower.

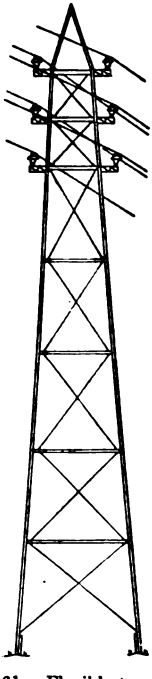
most of the work on it can be done by unskilled labor. The flexible towers as a rule come all assembled.

169. The design of a steel tower is largely the work of the structural engineer, but the electrical engineer should be able to specify the various stresses that the tower must withstand, the height, length of cross arm, etc., and be able to check the design by calculating the stresses in the various members. (See Pars. **131** and **132**.) Towers made with members which are too light, deteriorate very rapidly when corrosion once begins, and the cost of

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painting such towers, should this form of protection be found necessary, will be high. Members should never be much less than 3/16 in. (0.48 cm.) thick. Fig. 60 shows a standard tower, Alabama Power Co., designed for two 110,000-volt circuits and two ground wires. Members 1 and 2 and channel 3 below the ground line are part of the foundation and are designed to transmit the horizontal shear. (See Par. 132.) Fig. 61 shows a flexible tower.

170. Protection against corrosion is obtained by painting, galvanizing and sherardizing. For proper protection, paint must be applied every 2 or 3 years, and if the tower consists of a large number of small members, the expense of painting may be prohibitive. Where the structures consist of a few members, painting may be economically used. One coat of hot dip galvanizing, well applied, offers protection for perhaps 30 years, except at the ground line. A shell of concrete at the ground line may materially increase the life of the tower. Sherardising or "dry galvanising," gives a uniform coating at a low cost, and offers a high resistance to wear and abrasion. If the zinc is removed by abrasion or bending, the zinc-iron alloy still offers protection.



171. Erection of the tower is ordinarily by gin poles or by shear poles. The former device consists of a wooden mast or a frame which must be set outside the tower base. The butt must be firmly anchored, and the pole strongly guyed, especially in the direction of the back line.

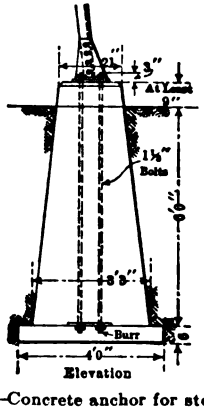


FIG. 61.—Flexible tower. FIG. 62.—Concrete anchor for steel tower.

The shear pole supports the raising line and affords a means of raising the tower by a straight away pull. The straight shear pole has a groove at the top, over which the raising line passes. The shear pole may be lowered to the ground when the raising line clears the top.

Heavy towers must often be braced at the base by some form of strut, to reinforce the tower against the stresses due to erection.

172. Special structures are often required for transpositions, and at points where the line crosses a river, a bay, or a railroad. They are also used where the line makes a sharp angle; where the line is dead-ended; and to allow the installation of line switches, protective apparatus, or outdoor sub-stations or switching stations. Special structures are usually very ex-

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pensive as compared with the standard towers, and where one of the latter will answer the purpose, it should be used.

173. Steel towers may be set directly in the ground, in which case the steel should be well protected by galvanizing. The footings are usually made by bolting an angle or channel iron directly to the bases of the anchor stubs. For the heavier structures, a built-up grillage is necessary. Fig. 62 shows a concrete anchor.

POLE ACCESSORIES

174. Wooden cross arms may be of either Norway or yellow pine, long-leaf yellow pine, Washington fir, though other woods such as cypress, oak, spruce and cedar are used to a limited extent. Long-leaf yellow pine, and Washington fir are the best woods for high-class construction, the average life untreated being 8 and 11 years. Wooden cross arms are being used in connection with steel or concrete poles. In certain localities, cross arms are being treated to prevent decay. The full-cell treatment (see Par. 151) is usually employed, although the initial treatment by live steam is found unnecessary if the arms have been well seasoned. Cross arms should be seasoned for at least 3 months and painted with two coats of white lead paint, unless properly treated with a suitable preservative. For the voltages employed in transmission work, there has been no standard size of cross arm adopted. In the lighter construction, the standard electric light cross arm, 3½ in. × 4½ in. (8.25 cm. × 10.8 cm.) often answers the purpose. For heavier work, sizes ranging from 4 in. × 5 in. (10.2 cm. × 12.7 cm.) to 5 in. × 7 in. (12.7 cm. × 17.8 cm.) are used.

Cross arms should be snugly fitted into a 0.75-in. (1.9 cm.) gain. Unless the pole previous to erection has been treated by some preserving process, the gain should be given a good coat of mineral paint. Cross arms may be secured to the pole by two lag bolts, though in the best construction the cross arm is supported with a through bolt and braces. The cross arms on alternate poles should face in opposite directions.

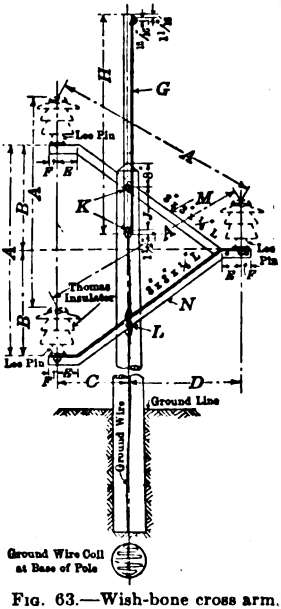


FIG. 63.—Wish-bone cross arm.

175. Cross-arm braces are discussed in Sec. 12, Par. 177 to 179.

176. Double cross arms should be used where very large stresses may occur such as at line terminals, corners, curves, and where extra precautions against life or property hazard are required, as at railroad, highway, or low-voltage line crossings. See Sec. 12, Par. 178.

177. The wish-bone and bo-arrow cross arms, made of angle iron, are used for wooden-pole, single-circuit construction. The ground wire is carried on the bayonet, at the tip of the pole. See Fig. 63.

178. Insulator pins are made of wood, of steel and of steel in combination with porcelain. Although the wooden pin adds to the insulation, the dielectric stress in the insulator is so localized, especially in wet weather, that little is gained; wood deteriorates rapidly, being carbonized by leakage currents, and eaten by nitric acid which forms in the presence of high voltages. Furthermore, a wooden pin is weaker mechanically than a steel pin, hence requires a larger hole in the cross arm, and thus decreases the mechanical strength of the arm. **Wooden pins** should be used only for the lightest construction, and with voltages not exceeding 20,000. They are made from

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locust, oak, maple, hickory and eucalyptus, and should have a fine straight grain, free from knots.

179. A wooden pin with a centre bolt is common. The bolt serves as a cross-arm fastening and the wooden portion holds the insulator. The advantage of this over a straight wooden pin is that a much smaller cross-arm hole is required.

180. Steel pins may be of steel, malleable iron, cast iron, cast steel, or combinations of these. They are much stronger than wood pins, and when well galvanized have a much longer life. They are either cemented directly into the insulator, with Portland cement, or capped with either a wooden or a lead thimble, which is screwed into the porcelain.

181. Clamp pins are designed to eliminate the weakening of the cross arm, due to removal of valuable material when holes are drilled for the insu pins. Furthermore, they reduce the concentration of leakage current, and hence the burning and charring of the wood.

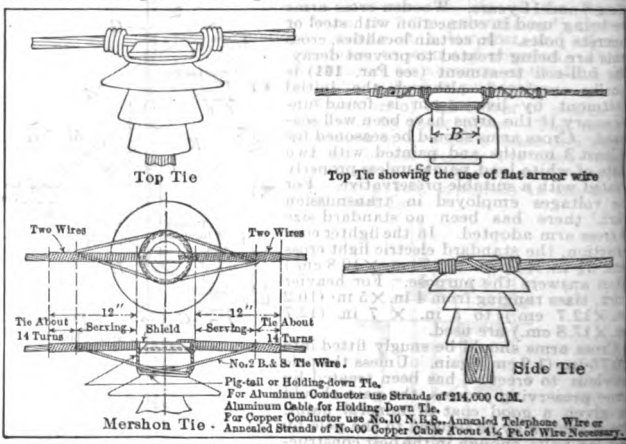


FIG. 64.—Insulator ties.

182. Insulator pins with a porcelain base (lead or wood thimble prevent an arc striking from the conductor to the pin, have a long life and are mechanically strong. Even though the porcelain cracks, the pin will only bend and the insulator will not fall.

183. Method of hanging suspension insulators. When suspension insulators are used, the breaking of a conductor pulls the string into a nearly horizontal position. The string should be able to swing freely in line with the unbroken span and the tower connection at the top of the suspension string should be made as snug as possible to the under side of the cross arm, to avoid torsion on the arm.

184. A tie wire or a clamp may be used to fasten the conductor to the insulator. The main function of a tie is to hold the conductor securely to the insulator, and prevent it from creeping from one span to the next. Its form depends largely on the type of insulator used. Aluminum tie wires should be used with aluminum conductors, as contact with other metals may form a galvanic couple and produce corrosion. Furthermore a harder metal will injure the soft aluminum. A large bearing area must be allowed where aluminum is used, as it is softer than iron or copper. No. 2, No. 3 and No. 4 A.W.G. have been found most satisfactory for aluminum ties. A few typical insulator ties are shown in Fig. 64, and Fig. 6 shows two Clarke insulator clamps.

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Owing to vibrations in the span, which are reflected at the points of support, aluminum strands tend ultimately to break at the tie when pin-type insulators are used. To prevent this, flat aluminum armor wire, usually 0.30 in. (0.76 cm.) wide and 0.05 in. (0.127 cm.) thick, is first wrapped around the conductor and the tie then made outside the armor as shown in Fig. 64. Flat armor wire is also used with suspension insulators, but the effects of vibration with this type of insulator are much less than with the pin type.

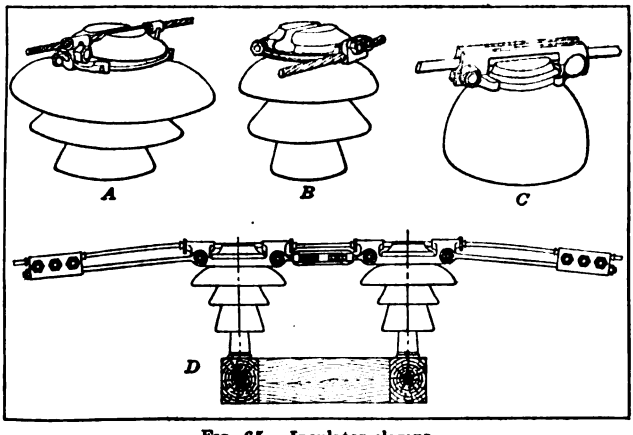


FIG. 65.—Insulator clamps.

185. Cable clamps for suspension insulators may be designed either to allow the cable to slip through and equalize the horizontal stresses in adjacent spans, or to hold the cable to approximately breaking loads, in case of a broken span. The clamp should be designed with a liberal cable seat and long, free, well-rounded approaches, so that the conductor will not be permanently injured if a span breaks, and the string is thus thrown temporarily into use as a strain insulator.

186. Suspension strain or anchorage clamps should admit the wire from the span without producing any kinks, or sharp bends, and should have a long, liberal bearing surface. The cable should not be held by such devices as U or J bolts, but rather by flat smooth surfaces.

POLE BRACES, GUYS, AND ANCHORS

187. Pole braces consist of shorter and lighter poles bolted against the main pole. They are sometimes preferable to guying, especially where a narrow right of way does not allow a guy wire to be used. The brace can be designed to take tension and compression; assist the main pole to resist the stresses in the direction of the line, and is not easily damaged maliciously. Owing to the increasing cost of poles, the cost of erection, and the liability of destruction by grass fires, guys are ordinarily to be preferred. Fig. 66 shows standard methods of bracing. The bearing area of the soil can be increased by fastening planks to the base, or by placing a flat rock under the butt. A log bolted to the butt also permits the brace to take tension. An A frame or double-pole, shown in Fig. 66b, may be substituted for the braced pole.

188. Guys are necessary to assist the supporting structure in resisting such unbalanced stresses as are produced at angles, terminals or on sloping ground. They are also used to give the line increased stability in places where a failure is very undesirable, where a hazard to life or property must

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be avoided, as at a railroad crossing, or where a line runs parallel to or crosses a highway. Steel towers are seldom guyed, their resistance to overturning being sufficiently large (also see Par. 133 and Sec. 12, Pars. 174, 175, 176). Well-galvanized steel strand should be used for guys. See table Par. 104.

189. **Straight-line guying** is used to give increased stability to the line. Approximately every twentieth pole should be guyed, in the direction of the line, either by head or anchor guys, and, if possible should be side guyed as well. Head guys should be used when a line runs over abruptly sloping ground, in order to give the line increased longitudinal stability.

190. **Guy anchors** are necessary where there are no trees, poles, or rocks to which the guy line may be conveniently attached. The simplest and most reliable form of anchor is the so-called "dead man," which consists of

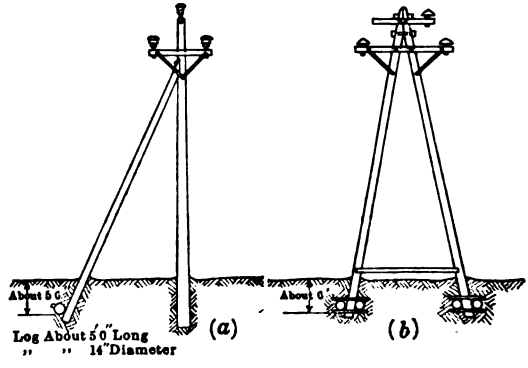


FIG. 66.—Pole brace. A-frame.

a log, 8 to 15 in. (20 to 38 cm.) diameter and 5 to 12 ft. (1.5 to 3.7 m.) long. A guy rod is passed through and held by a nut and washer. The log is buried to a depth of from 4 to 7 ft. (1.2 to 2.1 m.), depending on the load it must carry, and the character of the soil. Malleable iron plates may serve the same purpose.

191. **Patent anchors.** The many types of patent anchors depend for their holding power upon projections that are brought into play upon reversal of stress. The anchors are placed in position by being driven, screwed, or buried in the ground.

192. **Rock anchors** are often desirable where ledges or large boulders are encountered. They are made by setting an eye-bolt into the rock with or without cement, depending upon the character of the rock.

CONDUCTOR CONSTRUCTION

193. **Wire stringing** may be accomplished either by securing the end of the wire and carrying the reel forward, or by maintaining the reel stationary and carrying the end of the wire forward. The former method is best adapted to light construction and long lengths, whereas the fixed reel is best adapted to heavier construction and shorter lengths. The conductors are drawn up by means of a team, and when the proper sag and tension are obtained, the wires are attached to the cross arms by snub-grips, thus making temporary dead-ends which remain until the lineman can attach the clamps or make the tie. Where flexible or light structures are used, these must be guyed temporarily until a permanent line anchorage is made.

194. **Phase wires may be arranged** (Fig. 67) (a) in a horizontal plane; (b) in a vertical plane; (c) at the vertices of an equilateral triangle; (d) at the corners of a square (quarter-phase); and (e) at the corners of an isosceles

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triangle. Only in (e) are the conductors symmetrical with respect to one another. In the other cases, except (d), the inductive drop and charging current are unbalanced, but these effects are so slight that they can be neglected. The arrangement of circuits on a pole will be determined by mechanical considerations and the type of construction employed. When making inductance and capacitance calculations, the *average distance* between wires, or the cube root of the product of all three of the actual distances may be used. Either method introduces only a slight error. For spacing and clearances see Fig. 56.

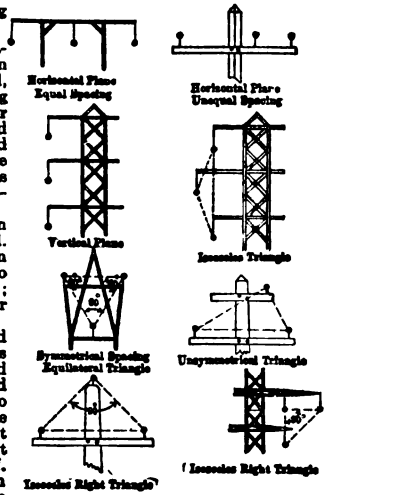


FIG. 67.—Grouping of phase wires.

196. Cable splicing. The insulation should be carefully removed from the ends of the cable to be spliced, close attention being given to getting the copper perfectly clean. A copper sleeve of the proper size may be used to make the joint. The joint should be left smooth and free from any little points of solder or sharp edges, as these factors tend to produce abnormal dielectric stress.

All burned or imperfect material in the insulation should be removed. The braid and tapes should be taken back far enough to allow the splices to be completed without touching them; this is very necessary owing to their low insulating properties.

The insulation should be beveled down to a very thin edge until it has the appearance of a well-sharpened lead pencil; this bevel or taper should be very gradual. If the taper is too short, it will be difficult to put the splicing compound on with sufficient density where the insulation stops at the joint, or at the end of the scarf. More high-tension joints break down at this point than at any other one place. The remedy is a very long, gradual taper or scarf.

When possible, a good rubber cement should be used, smearing the taper as far up on the insulation as the splicing compound is to go, keeping it off the copper. The cement should be allowed to dry out until all moisture has disappeared, leaving it firm and sticky. Enough pure rubber should be put on to cover the copper, running about one-third of the way up on the taper. This should be covered with a good rubber splicing compound until it is somewhat larger than the rest of the cable. Care should be taken to put as much tension on the splicing compound as it will stand, in order to get it on tight, to exclude all air and make the whole a solid, dense mass. In the case of submarine cables, the vulcanising of all patches and splices is recommended.

On small stranded joints, which must be kept flexible and which cannot be soldered, a layer of tin-foil over the joint is recommended; this should be laid on before the rubber is applied, and will prevent any corrosive action of the sulphur in the rubber on the unsoldered joint. (Also see Sec. 12, Par. **216.**)

196. Joints in transmission lines are seldom made up from the conductor itself but are almost entirely patented devices. Aluminum is not readily soldered and hard-drawn copper becomes annealed when soldered. The Western Union joint is used only for small wires. The so-called dovetail splice is made by fitting the strands of one cable between those of the other and wrapping one strand at a time tightly around the others and around the cable. The parallel-groove clamp is used where a jumper connection or station connection is to be made.

197. The McIntyre joint is used chiefly on small sizes of cable, although it has been used on sizes as large as 650,000 C.M. It is made of seamless

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copper or aluminum tubing, oval in section, into which each conductor is pushed from opposite ends, until the conductors project about 2 in. beyond the ends of the sleeve. The tube is then twisted three or four complete turns by special tools. This joint is efficient both electrically and mechanically.

198. For steel-reinforced aluminum, the simple McIntyre joint can be used in sizes up to 4/0, and develops about 80 per cent. the entire strength of the cable. For larger sizes, a 2-piece compression joint, using a steel McIntyre joint for the core of the cable, is recommended. The aluminum part is threaded together in the middle and the ends are compressed on to the cable by means of a portable hydraulic jack. Anchors should be of thoroughly galvanized malleable iron clamps, which hold the aluminum and steel core separately.

199. Ground-wire construction. See Par. **60, 91.** Ground wires are designed primarily to protect the line from lightning disturbances, and should be placed well above the line conductors. With wooden poles, the so-called "bayonet" shown in Fig. 63 is commonly used. This may be a piece of angle iron or a pipe properly drilled and fitted to be fastened to the pole top to receive the ground wire. Where steel towers or poles, and consequently long spans, are used, the ground wire is often depended upon to take up some of the unbalanced stress due to the breaking of a line conductor. This is especially true when flexible towers with pin insulators are used. A ground wire is absolutely necessary to hold these towers in the correct longitudinal position, if suspension insulators are used. Some companies mount the ground wire on insulators as an extra conductor during the winter. The ground wire should be held securely to the pole top by a clamp which is slightly flexible, has a grip of several inches, and flaring, well-rounded approaches. Taps to ground connections should not be soldered, but rather fastened by well-designed clamps. The wire should be grounded at every steel pole or tower by contact with the metal work. If the metal work is completely imbedded in concrete at the base, the ground should be made by driving an iron pipe, about 6 ft. (2 m.) long and 1 in. (2.5 cm.) diameter, into the ground, and connecting it to the metal work with a copper wire.* If the soil is dry, the ground can be made more permanent by pouring salt water around the pipe. When wooden poles are used, the ground connection should be made at every pole, by running a copper wire down the pole and grounding to a pipe driven in the ground, or by coiling the wire (bare) in a flat helix and placing it under the pole-butt.

200. Transpositions† are made to eliminate electrostatic and electromagnetic unbalancing of the various phases; to eliminate mutual induction between parallel lines; and to prevent disturbances in neighboring telephone and telegraph circuits. When used solely to improve operating conditions of the power line, the distance between transpositions may vary in different lines from 2 to 40 miles. When used to reduce disturbances in neighboring telephone and telegraph circuits, the distance between transpositions is determined by the irregularities of the parallel, the characteristics of the telephone line, etc. Generally it is of the order of magnitude of one mile. Fig. 68 shows the transposition of a section of three-phase line and a telephone circuit.

201. Transpositions are commonly made by rotating the delta; by gradually changing the relative positions of the wires; by dead-ends and jumpers, similar to the method employed in telephone work. The first method requires special structures that are usually interspersed between the standard towers. When the wires are arranged at the corners of a triangle, the delta is rotated through 60 deg. in one span, and through another 60 deg. in the next span. This is shown in Fig. 69 (*a*). When the wires all lie in the same plane, resort to an intermediate triangular arrangement

* Creighton, E. E. F. "Ground Connections in Lightning Protective Systems." *G. E. Review*, 1912, pages 12 and 66.

† Fowle, Frank F. "The Transposition of Electrical Conductors." *Trans.* A. I. E. E., Vol. XXIII (1904), p. 659.

Osborne, Harold S. "The Design of Transpositions for Parallel Power and Telephone Circuits." *Trans.* A. I. E. E., Vol. XXXVII (1918), p. 897.

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must be made, as shown in Fig. 69 (*b*). Both of the above methods require special structures, and the transposition spans are usually about one-half the length of standard spans, in order that proper clearance between conductors may be maintained. The jumper method, shown in Fig. 69 (*c*), requires only a standard strain tower, which may be slightly modified if the conductors happen to lie in a vertical plane. It is frequently possible to affect transpositions using only standard towers and spans.

202. A telephone line is essential to the satisfactory operation of every transmission system, as a means of communication between generating stations, sub-stations and patrolmen. When possible, the telephone wires should be run on a separate pole line to eliminate disturbances and trouble caused by the high-tension circuit. The cost of an extra pole line is often prohibitive, so it then becomes necessary to carry these wires on the power

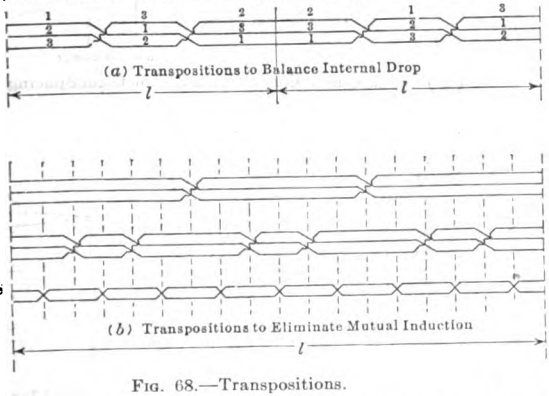


FIG. 68.—Transpositions.

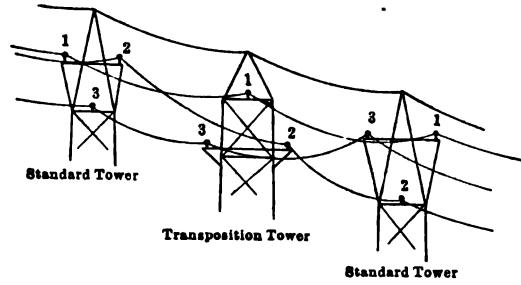
line poles or towers. In this case they should be at least 8 ft. (2.44 m.) beneath the nearest power wire, and in as protected a position as possible. Otherwise the telephone may be rendered useless when trouble occurs on the power line—a time when the telephone is most needed. Small telephone wires may be unable to withstand the stresses in occasional long spans. In this case they may be supported by a steel messenger wire, and if this latter is grounded, it helps to shield the telephone wires from inductive effects.

203. Induced electrostatic charge may raise the potential of the telephone circuit to a dangerous value. This potential can be greatly reduced by connecting coils of low reactance to ground, known as **drainage coils**, across the telephone line at intervals, and grounding their middle points. For further protection to the user, vacuum lightning arresters, horn-gaps, fuses and well-insulated transformers are used. Some companies have found the vacuum gap arresters unreliable, owing to the loss of vacuum when in use, and have replaced them by other types, such as the knurled cylinder type.* Fig. 70 shows the connections ordinarily employed.

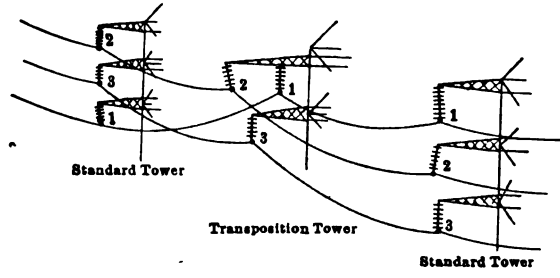
204. Where overhead crossings are made, as over railroads or high ways, extra precautions are necessary to protect life and property. In the past, a grounded cradle or basket-work beneath the lines, or some other grounding device, has been used to catch and ground the falling conductor. Present-day practice rests on the principle that the less there is to come down, the better, and further assumes that there shall be no broken conductors. Safety is now procured by the use of short, well-supported spans, and by using an increased factor of safety for the materials employed. See National Electrical Safety Code.

* Gillespie, F. M. *Elec. Wld.*, LXVI, 1915, p. 1315.

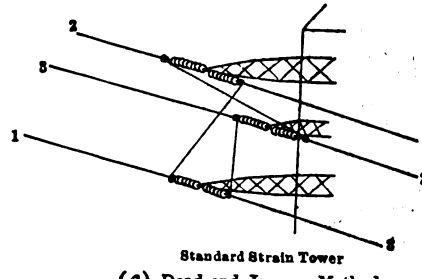
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(*a*) Single Circuit Construction-Symmetrical Spacing



(*b*) Vertical Spacing

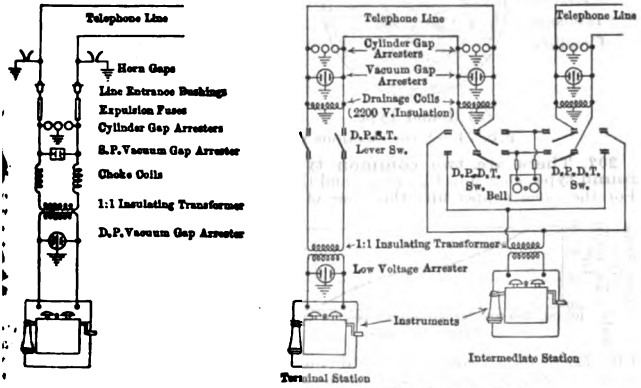


(*c*) Dead-end Jumper Method

FIG. 69.—Methods of transposition.

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205. Extra precautions in overhead-crossing construction.* No allowance shall be made for deformation, deflection, or displacement of the supporting structures. In computing the longitudinal stresses upon conductors and their supports, and the sags corresponding to given limiting stresses in conductors, the loading shall be assumed as one of the following, according to climatic conditions of the locality: Heavy loading; conductor plus 0.5 in. (1.27 cm.) radial thickness of ice and horizontal wind pressure of 8 lbs. per sq. ft. wind pressure. Minimum temp. 0° F. Medium loading—2/3 heavy loading, but in no case less than 25 per cent. in excess of weight of conductor. Minimum temp. 15° F. Light loading—2/3 medium loading, but in no case less than 25 per cent. in excess of weight of conductor. Minimum temp. 80° F.



(a) Without Drainage Coils (b) With Drainage Coils

FIG. 70.—Telephone protection.

Under the preceding loads assumed, the calculated stresses in the steel members and in the guys shall not exceed the following values:

Structural steel	
Tension	27,000 lbs. per sq. in.
Shear	24,000 lbs. per sq. in.
Compression	27,000 L/r
Bolts, rivets, pins	
Shear	24,000 lbs. per sq. in.
Bearing	48,000 lbs. per sq. in.
Bending	36,000 lbs. per sq. in.
Guys	One half the ultimate strength.

Poles or towers supporting the crossover spans of overhead supply lines over railways shall, unless physical conditions or municipal requirements prevent, have side clearance not less than 12 feet from the nearest track rail, except that at sidings a clearance not less than 7 feet may be allowed.

The clear space between the lowest overhead supply line conductor or wire and the heads of rails above which the former cross shall not be less than the following at 60° F., with no wind, where the conductor or wire has fixed supports and the span does not exceed 150 feet and where men are permitted on cars.

300 volts to ground to 15,000 volts, 28 feet.
15,000 volts to 50,000 volts, 30 feet.

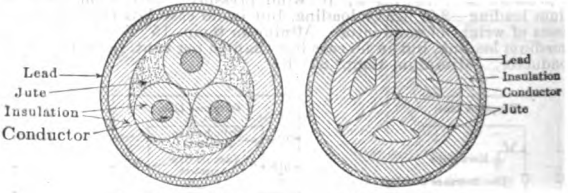
* National Electrical Safety Code, Third Edition, 1920, p. 139.

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For longer spans they shall be increased 1 inch for each 10 feet of the excess between 150 and 300 feet and by 1 inch for each 20 feet of the excess beyond 300 feet.

HIGH-TENSION CABLES

206. Underground and submarine cables are often used for transmission purposes. Pressures up to 60,000 volts are successfully employed.



(*a*) Round Type. (*b*) Sector Type

FIG. 71.—Cross-sections of high-tension cables.

207. There are two common types of high-tension cables, the **round type,** shown in Fig. 71(a), and the **sector type,** shown in Fig. 71(b). For the same copper and thickness of insulation the sector type has the smaller diameter, as shown in the plot, Fig. 72. The relation of copper areas in the two types, for fixed diameters and thickness of insulation, is shown in Fig. 73 (Simplex Wire and Cable Co.).

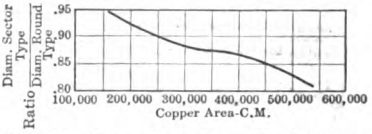


FIG. 72.—Comparison of outside diameters, sector and round types of high tension cables.

208. The essential characteristics of high-tension cable insulation are: high insulation resistance; high dielectric strength; low permittivity or dielectric constant; and low dielectric loss.

Insulating Materials. Three types of insulation are in common use: (*a*) rubber compounds; (*b*) varnished cambric; (*c*) impregnated paper.

209. Rubber compounds consist of Fine Para or Smoked First Latex Hevea rubber and such mineral ingredients as sulphur, whiting, talc, and litharge. A good high-tension rubber compound has a higher dielectric strength, higher permittivity or dielectric constant, and greater dielectric loss than either varnished cambric or paper. It can be used for submarine cables without a lead sheath. Rubber compounds are seriously affected by ozone. Rubber-insulated cables require very careful construction and installation to prevent the formation of corona and its resulting ozone.

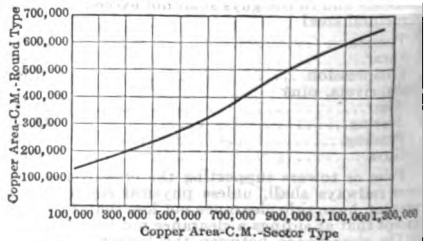


FIG. 73.—Comparison of copper areas, sector and round types of high tension cables with same outside diameter and thickness of insulation.

210. Varnished cambric insulation consists of a closely woven cotton cloth and a viscous filler. Each surface of the cloth has several smooth, continuous films of insulating varnish. The filler is a viscous, moisture-

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repelling, insulating compound, and has a dielectric constant practically equal to that of the varnished cloth; it prevents the tapes from unwrapping when cut, and is of such a nature as to allow the layers to slide upon one another when the cable is bent. The varnished cloth is applied in the form of tape wound on helically, the filler being applied between layers.

Varnished cambric has high dielectric strength, is not affected by ozone or corona, and is not easily overstressed. It is well adapted to high tension work. Varnished cambric cables are more flexible than paper cables, more easily jointed and can be installed at lower temperatures with less risk of injury. They can be submerged several hours without absorbing moisture. This allows them to be used extensively with a braided covering only. They are well fitted for service where the temperature is so high as to make rubber insulation unsuitable, or where surges in the voltage takes place. When lead-covered and armored, they make excellent submarine cables.

211. Impregnated paper insulation consists of manila paper applied helically, firmly and evenly to the conductor and then thoroughly impregnated with an insulating compound. Before impregnation, the paper insulation must be thoroughly dried.

The value of the paper as a dielectric depends mostly upon the composition of the impregnating compound. It should have high dielectric strength, low dielectric constant, low dielectric loss, should retain its insulating qualities at high temperature, should be sufficiently viscous at high temperature to prevent flow from one part of the cable to another, and sufficiently fluid at low temperatures to allow bending of the cable.

Cables insulated with impregnated paper usually have high dielectric strength, and have lower capacitance and lower dielectric loss than cables insulated with either cambric or rubber insulations. Impregnated paper can be operated safely at higher temperatures than the other types of insulations. Paper cables require a lead sheath, and successful operation depends upon the integrity of the sheath.

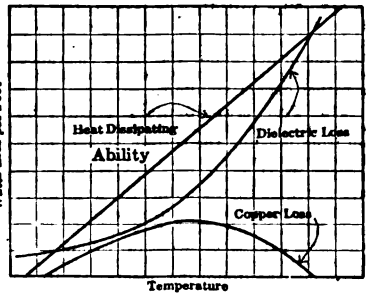


FIG. 74.—Effect of dielectric loss on allowable copper loss.

212. Dielectric loss is an energy loss which occurs in the dielectric of a cable. In cables for voltages less than 7,500 volts, this loss is negligible. Fig. 74 shows the effect of dielectric loss on the current-carrying capacity of a cable. The allowable copper loss is the difference between the heat dissipating ability of the cable and the dielectric loss.

Below are given what are considered as normal values of no-load power-factor and dielectric loss per foot of cable at different temperatures for 3-conductor cables operating at 13,000 volts and higher. Dielectric loss data are meagre and little has been done as yet in the matter of standardizing dielectric losses in cables.

Temperature, deg. cent.	Power-factor	Dielectric loss, watts per foot
20	.01 to .015	0.04 to 0.05
40	.025 to .07	0.10 to 0.15
60	.06 to .10	0.25 to 0.30
80	.15 to .20	0.50 to 0.80
100	.20 to .30	1.00 to 1.50

The above figures are for cables having low dielectric losses.

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213. Maximum temperature. As recommended by the A. I. E. E., the maximum safe temperatures in degrees cent. at the surface of the conductor in any cable is:

For impregnated paper insulation..... $(85-E)$
For varnished cambric..... $(75-E)$
For rubber insulation..... $(60-E/4)$

where E is the operating phase voltage in kilovolts.

214. High voltage cable testing.* High voltage tests should be applied between conductors, and between conductors and sheath. The test voltage E is determined by the formula $E = Kd \log_{10} D/d$ where D is the diameter over the insulation, d the diameter of the copper, and K a constant depending on the dielectric strength of the insulating material.

215. Electrical disadvantages of a cable system. A cable system differs from an overhead system in that the capacitance is much greater while the linear inductance is negligible. Hence the charging current may be equal to or even greater than the load current itself. Surges and transient phenomena are much more common than in an overhead line of the same length.

216. Underground cables for high-tension work are ordinarily installed in standard ducts (see Sec. 12). All underground cables should be **lead covered.** The rubber covering may last for years after the lead sheath has been eaten away by electrolysis or has been injured mechanically.

SUB-STATIONS†

217. The building is intended to shield the apparatus and equipment from the weather, as well as to furnish a shelter where repairs may be quickly made. A low-voltage station may have a fairly low initial cost. On the other hand, the large clearances required by overhead bus-bars, connecting-leads, arrester equipment, etc., make the high-voltage sub-station a rather expensive affair.

218. The transformers should be installed in separate fireproof compartments which should be of such construction as to prevent burning oil from flooding the station, in case of trouble. Provision should be made for easily moving the units, so that repairs and replacements can be quickly made. Each transformer is often installed on wheels and rails, and trucks are provided in order that the large units may be readily moved.

219. Protective equipment is often placed indoors. The larger sizes of aluminum arresters and the large overhead clearances required for the horn-gaps often necessitate that these, as well as the aluminum arresters, be placed out-of-doors. Where there are no overhead busses or inflammable material, the following clearances from the top of the horns should be allowed: for pressures up to 16,100 volts, 3 ft. (1 m.); from 16,101 to 37,900 volts, 4 ft. (1.2 m.); from 37,901 to 70,000 volts, 6 ft. (2 m.). At pressures above 70,000 volts, the horn-gaps should never be placed indoors. The auxiliary charging gaps for the aluminum arresters, when charging, should always be in sight of the operator.

220. Choke coils are often mounted on post insulators on the outside of the building, especially where very high voltages are employed. For the lower voltages they may be conveniently installed on the inside wall, or directly in the switch leads.

221. High-tension bus bars are hung from the ceiling by suspension insulators, are suspended by ceiling insulators, or are mounted on post insulators. Owing to their low cost it is desirable to utilize suspension insulators whenever possible. Fig. 75 shows typical high-tension bus construction. (See Sec. 10, Par. **869**.)

222. Entrance and outlet for lower voltages are as shown in Fig. 76. Plate glass with a central hole, slightly larger than the conductor, is often

* Middleton and Dawes. "Voltage Testing of Cables," *Trans.* A. I. E. E., Vol. XXXIII (1914), p. 1185.

† See Sec. 12, Par. **51**.

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used, as it keeps the weather out. Where high-voltage must be carried into a station, great care should be used in the design and selection of suitable bushings. A simple entrance for a 110,000-volt line consists of a 5-ft. (1.5 m.) slab of glass or marble, with a small hole sufficient to admit the conductor without undue corona discharge. In Fig. 77 are shown typical wall bushings.

223. The condenser type* of bushing is built up by placing thin layers of tin foil between concentric layers of insulation, and making the areas of the foil equal, irrespective of the diameter, thus giving uniform potential distribution. Such a bushing is shown in Fig. 77 (c).

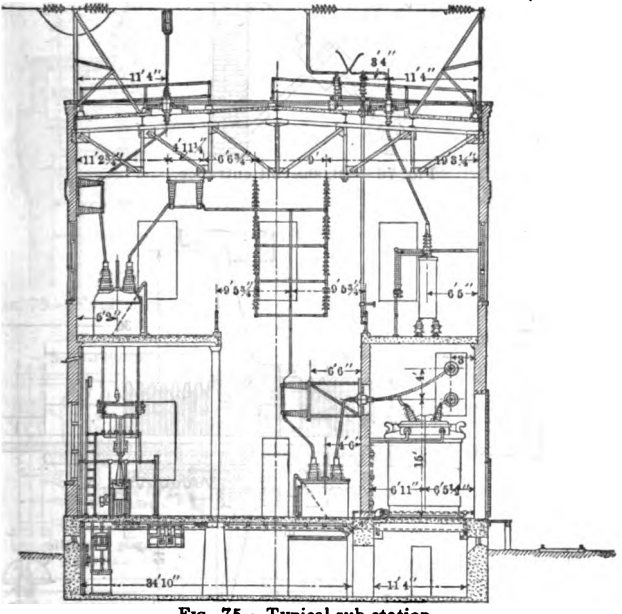


FIG. 75.—Typical sub-station.

224. Roof entrances and horn-gap outlets require a petticoated insulator in addition to a wall bushing in order to prevent trouble which might arise from rain and condensed moisture. The ratio of wet to dry flash-over should be very high. Fig. 134, Sec. 10, shows a typical roof insulator, and Fig. 78 shows standard roof construction.

225. A Sub-station wiring diagram is shown in Fig. 79, and Fig. 80 shows a typical instrument panel. Instrument leads A and B (Fig. 80) correspond to instrument transformer leads A and B (Fig. 79).

226. Outdoor switching stations are often installed at points where the amount of switching actually done does not warrant the expense of a building for housing the equipment. In such cases, a safe and economical construction is to erect a platform on a special structure, upon which the switch-handles, transformers and other equipment are placed.

* Reynders, A. B. "Condenser Type of Insulation for High-tension Terminals." *Trans.* A. I. E. E., Vol. XXVIII (1909), p. 209.

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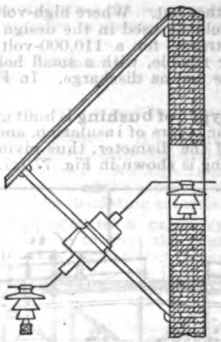
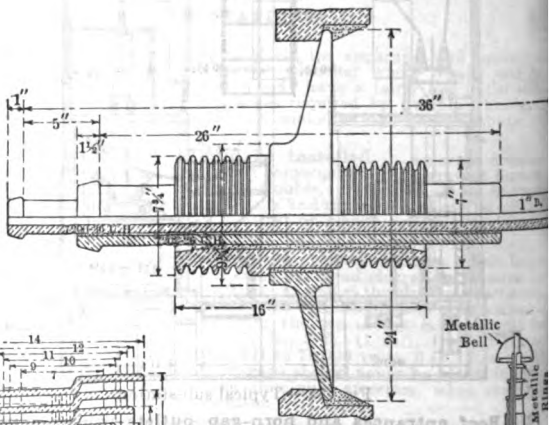
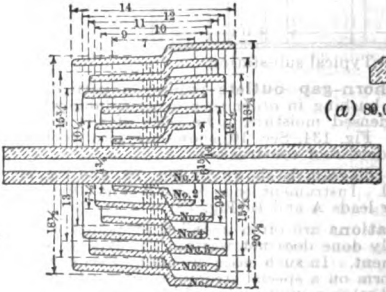


FIG. 76.—80,000-volt entrance.



(a) 80,000 Volts



(b) 90,000 Volts



(c) Condenser Type Bushing

FIG. 77.—High-tension bushings.

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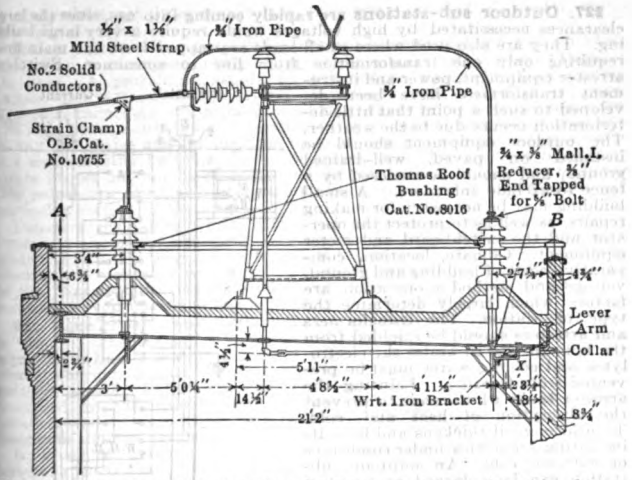


FIG. 78.—Typical roof construction showing horn gaps and roof insulators.

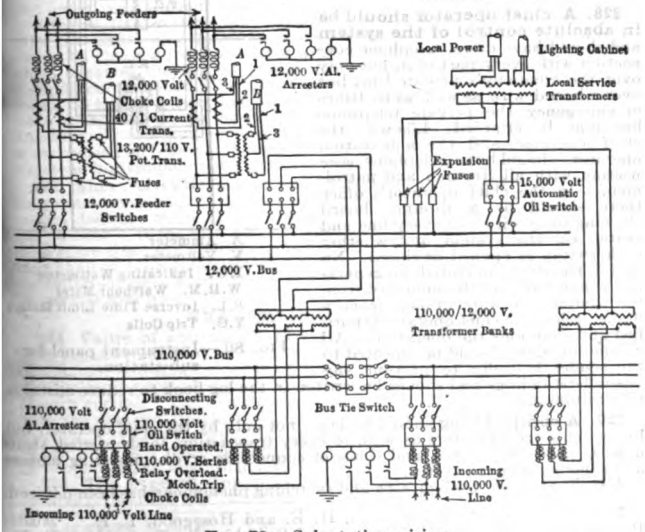
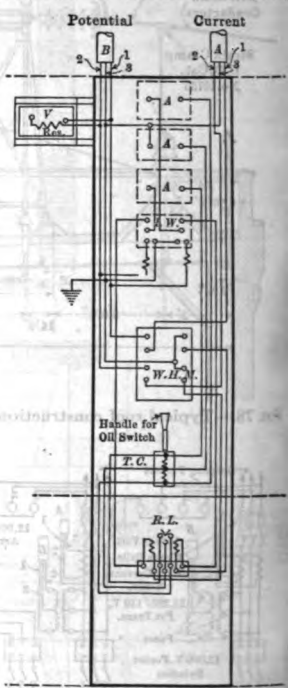


FIG. 79.—Sub-station wiring.

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227. Outdoor sub-stations are rapidly coming into use, since the large clearances necessitated by high voltages would require a very large building. They are also used where small loads are tapped from the main line, requiring only one transformation from line to consumer. Switches, arrester equipment, power and instrument transformers have been developed to such a point that little deterioration occurs due to the weather. The outdoor equipment should be installed on paved, well-drained ground, and should be enclosed by a fence to exclude intruders. A small building may be necessary for making repairs, as well as to protect the operator and the switchboard and meter equipment. Climate, location, comparative costs of building and ground, voltage and method of operation, are factors which largely determine the type of station. The transformers and arresters should be shielded from the hot sun, and in winter the electrolytes and cooling water must be prevented from freezing. Painting the arrester tanks white tends to prevent the absorption of heat and cold. Transformer oil thickens and loses its insulating properties under conditions of extreme cold. An outdoor substation can be enlarged or modified with but little expense.



A Ammeter
V Voltmeter
I.W. Indicating Wattmeter
W.H.M. Watthour Meter
R.L. Inverse Time Limit Relays
T.C. Trip Coils

FIG. 80.—Instrument panel for sub-station.

OPERATION

228. A chief operator should be in absolute control of the system and should have direct telephone connection with every part of it, not only over the company's private line, but over a leased wire as well, as in times of emergency the private telephone line may be crippled. Likewise the chief operator and the sub-station operators should be in telephone connection with all linemen and patrolmen. In the chief operator's office there should be a dummy board showing the position of every line and switch on the system and whether each switch is opened or closed. No switch should be operated, no generator connected to or disconnected from the system, no water taken from a flume, unless the chief operator is notified and sanctions the operation. All communications should be repeated to the sender in order to prevent any misunderstandings and should be written in the log book to reduce mistakes to a minimum.

229. A complete log should be kept, not only by the chief operator, but by switchboard operators as well, of every transaction, loads carried, shutdowns, causes of trouble, and times of connecting or disconnecting motors and generators on the system.

A *multi-recorder** for lightning and switching phenomena has been devised,

*Creighton, E. E. F., Nichols, H. E. and Hosegood, P. E. "Multi-Recorder for Lightning Phenomena and Switching." *Trans.* A. I. E. E., Vol. XXXI (1912), p. 825.

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whereby the exact times of switching, shut-downs and disturbances are automatically recorded.

230. A periodic line inspection should be maintained over all lines, the frequency of inspection depending on the country and the importance of the lines. A patrolman should be assigned to about 20 miles of line, as one man is then always within 10 miles of each section of the line. The patrolmen may cover the ground on foot, on horse-back, with a horse and team or an automobile, depending entirely upon the nature of the right of way, his duties and the distance he must travel. The pole switches and line sectionalizing switches should be inspected at least once a month, to insure proper alignment of parts and proper operation in times of need. The patrolman should be held responsible for the proper operation of his particular section of the line.

Defective insulators which cannot be detected by inspection may be located by the use of a megger. A sound insulator should have a resistance greater than 1,000 megohms, whereas, if the porcelain or glaze is injured or cracked, the resistance will drop below 500 megohms. Other methods, such as the "buzz stick," "spark stick," etc., may be used to locate defective insulators, even when the line is in service. (See Par. **82.**)

231. Line repairs and replacements are often made only after the line is "dead." The lineman or patrolman should notify the chief operator when a particular line or section is desired. The line should then be cleared, not merely through the oil switches, but should be opened by disconnection switches as well. Before a lineman is allowed to work, the line should be wet grounded, in order to eliminate the electrostatic charge. If the line closely parallels another power line, both ends should be grounded to eliminate any dangerous induced potential.

In order to make repairs and replacements without interrupting the service, special tools, mounted on the ends of wooden sticks, have been devised whereby insulators may be replaced, conductors spliced, etc., while the line is alive.

232. Aluminum arresters* should ordinarily be charged at least once a day, under normal conditions of temperature. In hot weather, or if exposed to a higher temperature, they should be charged two or three times a day. After passing a heavy discharge, and undergoing a high temperature rise, they should be charged intermittently while cooling, in order to re-form the film, which dissolves very quickly when the temperature is above normal. The charging current should be about 0.4 amp. The auxiliary or charging gap should be closed three or four times or until the arc ceases to flare. Ammeter jacks are now available for convenience in measuring the charging current. An abnormal charging current may denote trouble within the arrester, such as carbonized oil between the cones. It is desirable to charge the arresters on a system, individually not all at the same time. (Also see Sec. 10, Par. **862.**)

233. Short-circuits may open the line when a station is provided with automatic breakers. Where non-automatic switches are used, the operator should decrease the voltage, rather than open the circuit, waiting for the line to clear. If the line does not then clear, the load should be thrown over to a spare line until repairs can be made. Where it is essential that the service shall not be interrupted, resort may be had to such expedients as operating single phase, with a ground return, etc., until the line is again in its normal condition.

TRANSMISSION ECONOMICS

234. Value of continuity of service. No system should be equipped with expensive automatic control devices, duplicate lines, liberal protective equipment, and spare generating plants in order to insure continuity of service, unless the cost of an interruption or a shut down justifies the expenditure of such capital. The line should be constructed as cheaply as is consistent with the required standard of service, without endangering life or property. Further, a system should not be extended to a distance greater than that at which there is a reasonable prospect of selling sufficient power to pay the development and operating costs of the extension.

235. The type of line must be decided upon after considering the reliability desired, the character of the country, transportation facilities,

*Creighton, E. E. F. "The Charging of Aluminum Lightning Arresters." *G. E. Review*, 1913, p. 248.

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availability of timber, etc. Although steel construction, as an engineering proposition, is far superior to wood, there are many instances where the low first cost of wood alone makes a transmission project economically feasible.

236. The length of span should be so chosen as to have the line cost a minimum. As the length of span increases, the number of supports and insulators decreases, but the height of the support and the conductor spacing must be increased to allow for the greater sag. The effect of these changes on cost for steel towers is shown in Fig. 81. Under these conditions, the most economical span for steel towers is about 700 ft. Other factors, such as the decreased cost for pole or tower rights on private right of way, the lesser number of insulators, with the increased possibility of failure with the longer span, should receive due consideration.

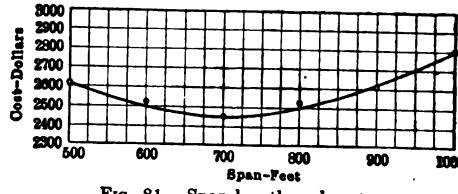


FIG. 81.—Span length and cost.

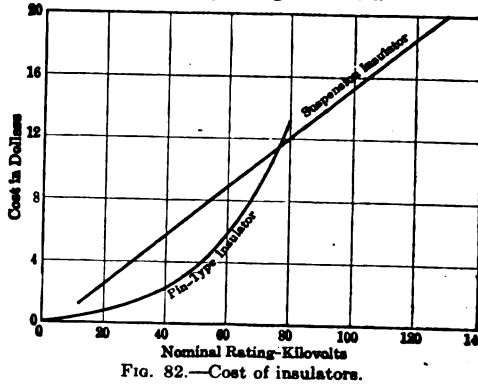


FIG. 82.—Cost of insulators.

237. The choice of conductor material lies between copper and aluminum, except for a few special spans. Although aluminum is about 10 per cent. cheaper than copper for the same conductance, its greater temperature coefficient of expansion and lower tensile strength demand greater sags, hence more expensive structures.

238. The size of conductor is influenced by mechanical considerations and by the amount of energy that it is permissible to waste in transmission. Line regulation may require a larger conductor than is economically demanded. When energy may be generated and sold at a low rate per kw-hr., a much smaller conductor is justified than if the reverse be true.

239. The choice of voltage is determined by the amount of power and the transmission distance. The conductor cross-section varies inversely as the square of the voltage, but the cost of insulators, supporting structures, stations, station protective equipment and transformers increases as the voltage is increased. These last three items are independent of the length of the line, so would make a higher voltage on a long line economically desirable, neglecting other considerations. Roughly, a thousand volts per mile seems to be

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the criterion adopted by engineers. An 80,000-volt line presents no greater operating difficulties than a 30,000-volt line. Surge voltages are, however, dependent upon the current and systems have been designed to operate at a higher voltage than is economically demanded, in order to secure greater freedom from surges.

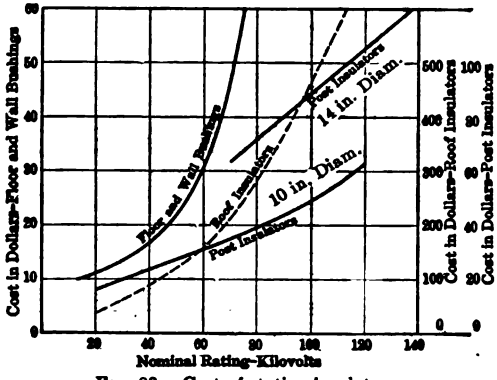


FIG. 83.—Cost of station insulators.

COST DATA

240. The trend of construction costs from 1914 to 1920 was continuously upward, and in the latter year peak prices of unprecedented character were reached for both labor and materials. The peak has now been passed and the trend is downward, but stable conditions have not yet been established. These important facts should be kept in mind in making use of the figures which follow, acknowledgement for which is due to the John F. Vaughan, Engineers, of Boston, Mass.

241. Estimated line costs per mile

COSTS PER MILE

Typical Lines in New Jersey

Estimate from actual construction records for cost per mile of 13.2 kv. wooden pole lines using 1914, 1918 and 1920 prices, open country. No special construction.

	1914		1918		March, 1920	
	One circuit	One add. circuit	One circuit	One add. circuit	One circuit	One add. circuit
Poles (45 ft.)	$1,200		$ 1,500		$2,000	
Cross arms, insulators and ground wire supports	900	500	1,100	600	1,500	650
Guying	400		500		600	
Right of way	200		300		400	
350 M.c.m. wire (3)	2,500	2,500	5,200	5,200	4,200	4,200
Ground wire	300		500		500	
Labor string wire	200	200	300	300	500	500
Incidentals	800	500	1,000	600	1,000	500
Totals	$6,500	3,700	$10,400	6,700	$10,700	5,850

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242. Cost Comparison of Typical Lines in Southern United States: per Mile
Data supplied by the John F. Vaughan Engineers, Boston.

Number of line	1	2	3	4
Voltage kv	44	44	110	110
Capacity kv-a	10,000	10,000	20,000	30,000
Length—miles	25	27.7	62.7	89.7
Date of construction	July–Oct., 1919	Jan.–April, 1920	July–Dec., 1919	Jan.–July, 1918
Conductors	#4 solid B.C.	3/0 Al SR cable	1/0 Al SR cable	250 M.c.m., SC
Insulators	Ohio brass 55 kv. pin type	Ohio brass 4 unit suspension	Ohio brass 7 unit suspension	Ohio brass 8 unit suspension
Ground wire	1⅝ in. steel	1⅝ in. steel	2⅜ in. steel	2 1/16 in. steel
Spans per mile	24	20	9	12
Poles	45 ft. chest.	45 ft. red cedar	50 ft. chest. (H-frame)	50 ft. creosoted pine (H-frame)
Cross-arms	4 in. × 5 in. × 6 ft.	4 in. × 5 in. × 6 ft.	6 in. × 8 in. × 29 ft.	6 in. × 8 in. × 29 ft.
Poles—(material)			$472	$578
Insulators—(material)	$920	$1,545	482	967
Hardware—(material)			350	603
Conductors—(material)	1,380	1,335	928	3,800
Poles and fixtures (labor)	250	448	715	918
Conductors—(labor)	158	208	240	388
Operation of stables and motor trucks	32	140	34	165
Camp and commissary	8	306		257
Moving and setting camps	90	256	100	270
Superintendence	250	192	297	355
Hospital and liability insurance				94
Incidental and miscellaneous	74	112	150	147
Overhead and expense	410	245	445	271
Engineering	30	82	18	78
Survey right of way	150	173	224	126
Purchase right of way	400	245	445	152
Clearing right of way	52	133	194	310
Total labor and material	$3,162	$4,542	$3,962	$8,852
Total right of way	3,764	5,093	4,631	9,130
Total overhead expense	4,294	5,420	5,094	9,479

NOTE:—Telephone line is included in each case; on [illegible] but along right of way, in Lines 3 and 4.

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243. Cost Comparison of Typical Lines in Southeastern United States: per Mile
Data supplied by the John F. Vaughan Engineers, Boston.

Number of line	1	2	3	4	5	6	7
Voltage	13,000	13,000	13,000	44,000	44,000	100,000	100,000
Length—miles	9.97	9.65	11.0	17.1	11.21	47.6	50.2
Type	Pole	Pole	Pole	Pole	Pole	Steel towers	Steel towers
Year built	1916	1916	1917	1910	1918	1913–14	1918
Conductors	3–#2 copper	3–#2 copper	3–#2 copper	3–#00 Al (copper equivalent)	3–#00 copper	6–#00 copper	6–#00 copper
Material costs:							
Structure (poles or towers)	$253	$240	$289	$167	$230	$1,410	$3,050
Cross arms and braces	103	68	82	46	92		
Insulators and pins	81	86	122	176	384	710	950
Hardware	14	20	27	41	32	64	97
Conductor	1,027	725	1,298	1,740	1,900	2,250	4,625
Ground	.....	.....	15	115	186	79	140
Telephone	.....	.....	.....	.....	16		
Bent and switches	.....	.....	.....	.....	.....	22	44
Sub total	$1,478	$1,139	$1,833	$2,285	$2,840	$4,535	$8,906
Labor costs	$419	$405	$695	$231	$1,073	$1,169	$1,833
Survey	38	23	99	39	35	60	37
Right of way	837	523	665	355	2,400	1,180	1,108
General overhead Expense	30	23	42	23	.....	31	23
Interest	36	42	41	.....	122	90	550
Supervision	.....	.....	1	.....	4	29	1
Total cost per mile	$2,838	$2,155	$3,376	$2,933	$6,474	$7,094	$12,458

Line 1.—Country district, 50 per cent. thickly wooded, average haul 3 miles. Line 2.—Sparsely settled, 20 per cent. lightly wooded, average haul 2 miles. Line 3.—Farming district, 40 per cent. thickly wooded, average haul 2 miles. Line 4.—Farming district, lightly wooded, average haul 2½ miles. Line 5.—Near large city, 30 per cent. lightly wooded, average haul 3 miles. Line 6.—Near several large cities, 40 per cent. heavily wooded, average haul 5 miles. Line 7.—Valuable farming district, 15 per cent. lightly wooded, average haul 2 miles.

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244. Cost Comparison of Typical Lines in California: per Mile
(Data supplied by the John F. Vaughan, Engineers, Boston, Mass.)

Number of line	1	2	3	4	5	6	7	8
Voltage kv	11	11	11	11	60	60	60	60
Length—miles	13.15	15.37	2.23	8.75	20.7	42.85	26.2	28.5
Type	pole	pole	pole	pole	pole	pole	pole	pole
Year built	1913–14	1918–19	1918–19	1918–19	1913–14	1913–14	1918–19	1918–19
Conductors	BC #4	BC#4 &#6	BC #6	BC #6	BC #1/0	BC #1/0	BC #4	BC #4
Insulators	brown porcelain pin #65	OB porce-lain pin #10044	OB porce-lain pin #10044	pin	brown porcelain #189 pin	brown porcelain #189 pin	OB#10566 Susp. 4 & 5 units	OB#10566 Susp. 4 & 5 units
Poles: No. per mile	15.25	14.97	23.3	17.0	18.79	15.84	15.11	15.6
Kind	30 ft. wood	35 ft. wood	40 ft. wood	30 ft. wood	40 ft. wood	50 ft. wood	50 ft. wood	50 ft. wood
Cross-arms	3 pin wide	3 pin wide	3 pin wide	3 pin wide	.....	2 pin wide	wishbone channel iron	wishbone channel iron
Guys: No. per mile	4.25	3.96	9.4	5.7	5.7	6.13	0.84	1.2
Character of country	mountain-ous	plains and level agric.	town alleys and streets	flat agric.	mountain-ous	flat agric.	flat agric.	plains and level agric.
Material	$621	$778	$796	$634	$1,535	$1,474	$1,452	$1,420
Labor	92	114	148	115	105	125	179	166
Transportation	42	54	78	41	247	102	76	90
Survey	24	2	.....	3	62	23	12	8
Right of way	45	none	.....	none	210	36	6	16
Overhead	78	143	147	119	279	255	257	253
Total cost per mile	$902	$1,091	$1,169	$912	$2,438	$2,051	$1,982	$1,953
Total labor and material	$713	$892	$944	$749	$1,640	$1,599	$1,631	$1,586
Total right of way	782	894	.....	752	1,912	1,658	1,649	1,610
Total all overhead	902	1,091	1,169	912	2,438	2,015	1,982	1,953

Lines 1, 5, and 6 built with teams to haul and deliver: linemen paid $3.50 to $4.00, groundmen $2.00 to $2.50.
Lines 2, 3, 4, 7, and 8 built with auto-trucks: linemen paid $5.25 to $6.00, groundmen $3.50 to $4.00.

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245. Cost of Typical Lines in Eastern Canada
(Furnished by Shawinigan Engineering Co. Ltd., Montreal, Que.)

Number of line	1	2	3	4	5	6	7	8
Voltage kv	25	66	66	66	110	110	110	110
Length—miles	18	13	14.25	38	86	22	8	86
Type	pole	pole	pole	pole	galv. st. towers	galv. st. towers	galv. st. towers	galv. st. towers
Year built	1916	1916	1918	1920	1911	1913	1916	1920
Conductors M. cir. mils	41.74 al. steel reinforced	#4 E.B.B. iron	#4 B&S. copper	150 al.	250 al.	200 al.	266.8 al. steel-reinforced	266.8 al. steel-reinforced
Insulators	27,000 volt OB 1265	Canadian porcelain #492	Canadian porcelain #492	pin type Canadian porcelain #2,260	7 unit suspensions	7 unit suspensions	7 unit suspensions	7 unit suspensions
Circuits	2 (only 1 erected)	1	1	1	2	2	2	2
Ground wire	none	none	none	none	2⅜" steel	2⅜" steel	2⅜" steel	2⅜" steel
Span ft	165	165	165	125	530	530	550	530
Type of base	.....	.....	.....	.....	concrete	concrete	concrete	concrete
River crossing	.....	.....	.....	.....	3	2	.....	3
Right of way	pole rights	pole rights	pole rights	pole rights	tower rights	tower rights	tower rights	
Cost per mile	$500	$330	$280	$1,100	$5,650	$275	$2,100	none
Line cost per mile	1,230	1,820	3,570	4,500 estimated	8,500	8,100	13,100	$16,500 estimated
Total cost per mile	1,730	2,150	3,850	5,600	14,150	8,375	15,200	16,500

Line 1.—About 20 per cent. of poles set in rock. Average haul 6 miles. Average price of labor $1.75 per day.
Line 2.—Average haul 3 miles. Average price of labor $2.50 per day
Line 3.—Average haul 4 miles. Average price of labor $4.00 per day. Labor inefficient and constantly changing.
Line 4.—Average haul 10 miles. Average price of labor $4.00 per day.
Line 5.—Fairly level ground. Average haul 5 miles. River spans about 1,200 ft.
Line 6.—No unusual construction features. River spans 1,300 ft.
Line 7.—Average haul 2 miles. Average price of labor $2.75 per day. Used as trunk line between two generating stations; heavy durable construction.
Line 8.—Average haul 5 miles. Average price of labor $4.00 per day. Same construction as line #5 and will parallel this latter line.

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246. Cost of cables per 1,000 ft.

2/0 stranded, 3-conductor—lead covered
(Simplex Wire & Cable Co.)

Volts	Underground			Submarine		
	Rubber	Cambric	Paper	Rubber	Cambric	Paper
6,600	$1,534	$1,458	$1,305	$2,229	$2,062	$1,974
13,000	2,373	2,357	1,584	3,260	3,115	2,334
25,000	3,880	3,634	2,165	5,008	4,564	3,087

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SECTION 12

DISTRIBUTION SYSTEMS

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SECTION 12

DISTRIBUTION SYSTEMS

CLASSIFICATION OF SYSTEMS

1. **Distributing circuits may be classified** as to the nature of the current—direct or alternating; as to method of connection—series or multiple; and further as to phase, number of conductors, voltage and frequency. The following is a statement of the field of application of the principal kinds of distributing circuits.

2. **Direct current** is best adapted to use: (a) where the distances are small, (b) where there is variable-speed machinery, and (c) where there is an area of congested load for which storage-battery reserve is necessary to insure continuous service.

3. **Alternating current** is best adapted to use where the distances are greater and the density of the load not sufficient to justify low-tension distribution without transformation from a higher voltage.

4. **The use of series systems** is limited almost entirely to street and other lighting which is all in use at the same time. These systems are inherently high-tension in character and are, therefore, not suitable for general purposes. They are operated by direct current or alternating current at a constant current of 5 amp. to 10 amp. in American practice. In Europe there are several direct-current series power transmission systems in operation utilizing a series of motor generators as the converting medium (Sec. 11).

5. **Multiple or parallel systems** are used for general purposes almost exclusively. When **direct current** is used a nominal voltage of 110, 220, or 550 is employed, the last named being used only for power distribution. The Edison three-wire system at 220 and 110 volts is common in large installations.

When **alternating current** is used, the primary mains are operated at a nominal voltage of 2,200. Single-phase, two-phase, and three-phase circuits are in general use, with frequencies of 25 or 60 cycles. In general, single-phase distribution is used for lighting and small power service, and two-phase or three-phase distribution is used for larger power loads.

6. **Frequency.** Twenty-five cycles is standard where most of the energy is converted to direct current for lighting and railway service or other purposes. Sixty cycles is standard where the energy is delivered for *retail* consumption as alternating current. Other frequencies such as 30, 33, 40, 50 and 133 cycles are in use in some of the older installations in America and in Europe. Sixty-two and one-half cycles is used in some modern systems where the supply is derived from a 25-cycle system, this frequency giving a better design of frequency-changer apparatus.

GENERAL APPLICATIONS

7. **The single-phase system,** requiring only the simplest form of electric circuit, has the advantage of a minimum number of conductors, and hence the minimum first cost for distributing mains. The feeders, however, require 33 per cent. more copper than equivalent three-phase feeders. Single-phase motors are more complicated and cost more than polyphase motors, and usually produce more disturbance of pressure, in starting, than three-phase machines. The distribution of energy by single-phase circuits is, therefore, usually limited to motor units of less than 10 h.p., although motors up to 35 h.p. are used in single-phase systems with good success. This system is used very generally for lighting circuits, in both single-phase and polyphase systems.

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8. Two-phase systems. Two-phase distribution is effected by the use of two single-phase circuits in a quarter-phase relation, making a four-wire system; or by means of a three-wire system in which one conductor of each phase is common.

The four-wire system is substantially the same as a single-phase system, except that two-phase motors may be used. The principal advantages of two-phase systems are that there are only two phases to keep balanced and only two transformers are required to supply polyphase energy to motors.

In a three-wire, two-phase system, the current in the common or neutral conductor is 1.414 times the current in the outer conductors, with balanced load. When all conductors are the same size, the copper required is 75 per cent. of that needed for a four-wire system. When the neutral is 40 per cent. larger than the outer conductors, the amount of copper required is 85 per cent. of that needed for a single-phase system or a four-wire, two-phase system. In the primary mains, which are all the same size, the three-wire two-phase system is as economical of copper as the three-wire, three-phase system. The line drop in this system is such that even with balanced load the drop in the two phases is not the same, making voltage regulation difficult, unless line-drop compensators are employed. The three-wire circuit cannot be used where the mid-points of the quarter-phase generator windings are tied together, as is the case in some machines.

9. Three-phase, three-wire system. This system is commonly employed for general distribution, since it is readily derived from a three-phase transmission system; it is also well suited to power distribution, and requires but 75 per cent. as much copper in the feeder system as an equivalent single-phase system. The three-wire distributing mains are usually carried only where motor service is required, the lighting service being taken on single-phase branches from the three-phase main. Users of small motors, up to about 5 h.p., are generally supplied from a single phase; while the larger motors, up to 30 h.p. or 40 h.p., are supplied from two phases with the open-delta connection.

10. Three-phase four-wire system. In primary distribution this system is usually operated at 3,800 volts between phase wires and 2,200 volts between any phase wire and neutral. This gives the advantage of 3,800-volt distribution in the feeder system and permits the supply of energy over a radius about twice as great as with 2,200-volt systems, with the same regulation. Standard 2,200-volt transformers and other accessories are used, and the lighting branches are single-phase. The unbalanced load is carried by the neutral wire, and with the use of line-drop apparatus, good pressure regulation is possible with any proportion of unbalanced load.

The four-wire distributing mains are carried only where there are motors or large loads to be served, and but three wires are needed for installations of less than 30 to 40 h.p., which may be served by two transformers connected in open delta. The wide range permissible has led to the adoption of this system in many of the larger cities of the United States. It is also well suited to the supply of suburban districts and rural communities, where double-voltage, 4,400–7,600 volts may be used to supply a group of towns and villages, the pressure being regulated independently on each phase at the source of supply.

11. Direct-current low-tension systems find their principal field of application in important parts of cities where the protection of the storage battery reserve is of great value, and where there are many elevators, printing presses and other variable-speed machines, and where space for transformers would be difficult to secure in public thoroughfares. The principal limitations of direct-current distribution are the small radius of distribution, and the necessity for rotating machinery to transform the energy from an alternating-current source of supply. This requires a greater number of substations to cover a given area, and these are more expensive both in first cost and operation than alternating-current substations.

12. Two-wire, 500-volt, direct-current systems are operated in some cities where they were originated to supplement single-phase systems in the early period of development. The duplication of mains necessitated by a separate power-service results in an excessive investment and 500-volt systems are being eliminated wherever possible.

13. Combination systems. Various combinations of alternating-cur-

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rent, and direct-current, or 25-cycle and 60-cycle systems, are necessary in the larger cities. The direct-current supply is usually derived through synchronous converters or motor-generators from an alternating-current generating system. The 60-cycle supply is sometimes derived from a 25-cycle system by the use of synchronous motor-generators called frequency changers. In some cases both 25-cycle and 60-cycle generating systems are maintained, and the frequency changers are used as a connecting link between the two systems.

TYPES OF CIRCUITS

14. Series circuits. Two general types of arrangement are employed in laying out series circuits, the "open loop," and the "parallel loop." In the **open-loop** circuit (Fig. 1) the lamps are connected by following the shortest available route, without reference to the separation from the return conductor. This permits a minimum length of circuit, but makes it difficult to test for a break, or open circuit in the line. In alternating-current circuits it also tends to increase interference with telephone systems.

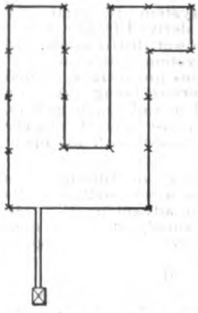


FIG. 1.—Open-loop series circuit.

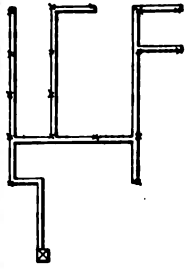


FIG 2.—Parallel-loop series circuit.

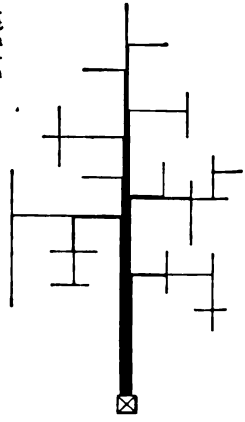


FIG. 3.—Tree-system of distribution.

The **parallel-loop** circuit (Fig. 2) is laid out in such a way as to be near the return conductor at many points. This affords frequent opportunity for test and minimizes inductive disturbances, but usually requires a greater mileage of conductor than the open-loop circuit. A combination of parallel loops with small open loops may often be used to advantage.

15. Multiple circuits. The arrangement of multiple circuits may take any one of a number of forms as conditions require. The simplest and least expensive circuit is that commonly known as the "tree" circuit (Fig. 3); it is thus named because it is branched off in various ways, and has its heaviest branches nearest the source of supply. The tree system is not adapted to supplying a uniform distribution pressure and is only suited to short branches and those branches in which the current values are small as compared with the conductor capacity.

16. A system of feeders and mains is the arrangement most commonly employed in city distribution for lighting and power-service. This takes the form of a network in low-tension systems (Fig. 4), and an isolated or dead-ended main system in primary distribution (Fig. 5). In the low-tension network the system of mains is designed to be of such capacity as to carry the load units which are tapped off from house to house, and the feeders are provided in such number, of such size and at such points as will maintain an even distribution of pressure, within a few per cent., over the entire system of mains.

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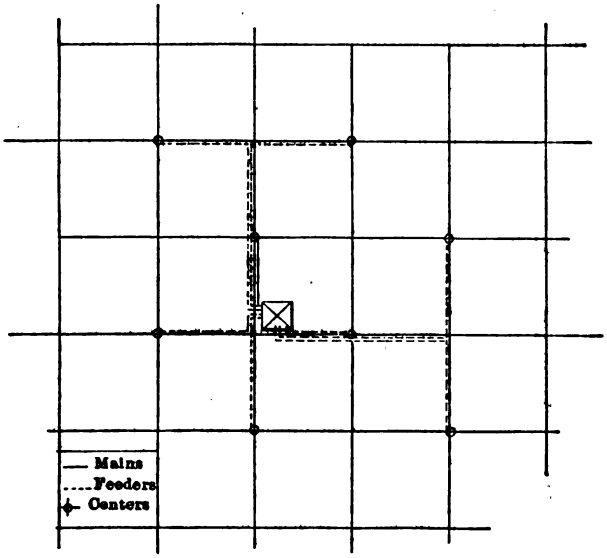


FIG. 4.—Feeders and mains in a direct-current network.

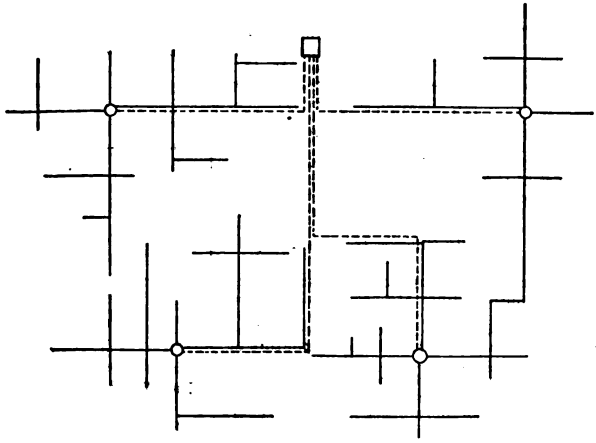


FIG. 5.—Feeders and mains in alternating-current distribution.

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17. **Primary-main systems** are usually supplied by a feeder at a centre of distribution, this point being a junction from which the load is distributed in four or more directions. These mains are not interconnected, because it is not practicable to provide fuse protection, and in most cases not much is to be gained by such connection.

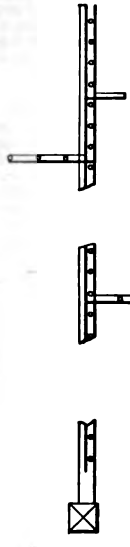


Fig. 6.—Loop feeder.

18. **The loop feeder** (Fig. 6), is used where the load is distributed in a long continuous line with few side branches. This arrangement distributes the pressure more evenly along the line than is possible with other types of circuit.

19. **Ring feeders.** Where it is desired to provide emergency supply to units of load in one general direction from the point of supply, the most economical means often consists of the type of feeder known as a ring circuit (Fig. 7). The capacity of the ring must be sufficient to carry the combined load of all the units, in case either of the links adjacent to the point of supply should fail.

20. **Urban transmission systems.** In cities having too large an area to permit an economical distribution of electrical energy from a single point, it becomes necessary to transmit energy from a generating station (located at a point convenient to coal and water supply) to substations centrally located with reference to the districts served. This transmission system, in the larger cities, becomes practically a bulk-supply distribution system. The same condition exists where hydroelectric energy is brought from a distance for distribution in a large city. These urban transmission systems are universally three-phase; where two-phase energy is generated, it is converted to three-phase energy for transmission.

21. **Pressures and frequencies in urban transmission.** The pressures in common use are 6,600, 9,000, 12,000, and 13,200 volts, and the standard frequencies are 25 and 60 cycles. The use of 25 cycles is preferable where the principal portion of the energy is converted to direct current for lighting and railway service, because the synchronous converter is more economical in operation and in first cost, at 25 cycles, than at 60 cycles. The use of 25-cycle energy for general lighting purposes is not satisfactory, and the transformers, motors, etc., are more expensive; hence it is necessary to convert the retail supply of alternating current to 60 cycles, to put it into form which is readily saleable.

The use of 60 cycles is desirable where the major part of the energy is to be distributed as alternating current. This permits the use of transformer substations, instead of frequency-changing motor-generators which are necessary for securing 60-cycle energy from a 25-cycle supply.

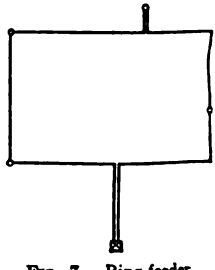


Fig. 7.—Ring feeder.

22. **Underground urban transmission.** Urban transmission lines are necessarily placed underground to a large extent. This involves the use of paper-insulated lead-sheathed cables, which are made up with the three conductors of the circuit under one sheath. With standard 3.5-in. ducts, the largest size of cable which can be drawn into the duct is about 3 in. with circular shaped conductors the largest size of conductor, of which three can be placed within a 3-in. lead sheath, is 350,000 cir. mils at 6,600 volts, or 300,000 cir. mils at 13,200 volts. With sector shaped conductors, it is possible to use three 500,000 cir. mil conductors at

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13,200 volts within a 3-in. sheath. This fixes the maximum load which can be carried continuously on such cables at from 4,500 to 8,000 kv-a.

In the larger cities where certain substations distribute loads of 8,000 to 15,000 kw., several cables are required to supply each substation, and it is desirable to have cables of the maximum size.

23. Reserve cables. A reserve cable must be provided for use in case of the failure of any of the cables which normally carry the load. This reserve may be secured by having a spare cable direct from the power-station, or by means of a **tie line** from a neighboring substation, or by the use of a ring system. When substation loads are small as compared with the cable capacity, the ring system is often found to be the most economical (Fig. 7). After the combined loads of the substations exceed the capacity of one side of the ring, additional capacity may be secured by adding **radial** feeders (Fig. 8). This is the situation in the larger cities where substation loads run from 2,000 kw. upward.

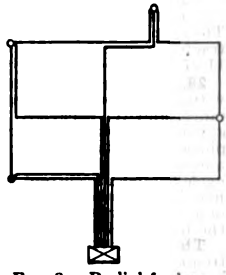


FIG. 8.—Radial feeders.

DESIGN OF CIRCUITS

24. General. The function of a conductor being to convey electrical energy from the source of supply to the consuming device, it must be of such size that it will not absorb too great a percentage of the energy or become overheated. The problem of designing a circuit is, therefore, one of determining what size of conductor should be used to limit the loss of voltage to a specified amount, when distance and current-strength are known, and also determining whether the size needed for the specified voltage drop is sufficient to carry the current safely.

25. Direct-current circuits. In direct-current circuits the current and the resistance are the only factors affecting the drop in voltage. The resistance of a mil-foot of pure annealed copper at 68 deg. fahr. being 10.4 ohms, that of a conductor D ft. long and M cir. mils in area is $R = (D \times 10.4)/M$. The drop with current I, therefore, is

$$E = IR = \frac{I \times D \times 10.4}{M} \text{ (volts) or } M = \frac{I \times D \times 10.4}{E} \quad \text{(cir. mils)} \quad (1)$$

If both conductors are of the same size the total drop is twice the drop in one conductor, as found by Eq. 1; if they are not of the same size, the drops in the different sizes must be computed separately and added together.

Example. A two-wire circuit is to carry a load of 100 amp. a distance of 300 ft. with a drop of 5 volts. What size of conductor must be used?

$$M = \frac{2D \times I \times 10.4}{E} = \frac{2 \times 300 \times 100 \times 10.4}{5} = 124{,}800 \text{ cir. mils.}$$

The nearest size is No. 2/0, A.W.G., which should be used.

26. The calculation of direct-current drop at any load is readily determined, where the size of the conductor is already fixed, by the use of the formula, $E = 2IDR/1{,}000$, in which R is the resistance per 1,000 ft. of conductor. The formula gives the total drop in the two wires of the circuit.

Example. A circuit of 4/0 cable, 500 ft. in length, is to carry a load of 190 amp.; what will be the line drop? The resistance of No. 4/0 conductor is 0.049 ohm per 1,000 ft. (Par. 21); $D = 500$ ft. The drop is

$$E = \frac{2 \times 190 \times 500 \times 0.049}{1{,}000} = 9.3 \text{ volts.}$$

27. Three-wire direct-current circuits. In making calculations for a **three-wire Edison circuit**, separate computations are made for each conductor if the load is appreciably unbalanced.

Example. A circuit having two No. 4/0 A. W. G. outer wires and a No. 0 **neutral**, 1,000 ft. long, carries a load of 150 amp. on the positive side and 110 amp. on the negative side; what is the drop on each side of the circuit?

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The resistance of 1,000 ft. of No. 4/0 = 0.049 ohm, and that of No. 0 = 0.098 ohm, per 1,000 ft. (Par. 21).

$E = IR = 150 \times 0.049 = 7.35$ volts drop on positive wire;
$E = IR = 110 \times 0.049 = 5.4$ volts drop on negative wire;
$E = IR = 40 \times 0.098 = 3.92$ volts drop on neutral wire.

The drop in the neutral wire is added to the drop on the "heavy" side and subtracted from that on the "lighter" side, making the total drop $7.35 + 3.92 = 11.27$ volts on the "heavy" side, and $5.4 - 3.92 = 1.48$ volts on the other side.

28. Alternating-current circuits. In an alternating-current circuit, voltage drop is caused by the combined effect of (a) resistance, (b) inductance, and (c) capacity. **The component of drop due to resistance** is governed by the same laws which govern direct-current circuits, and is in phase with the current. **The component due to inductance** (reactance drop) is a counter e.m.f. set up by the magnetic field and is a quarter cycle behind the current wave. The resistance drop and the reactance drop may be represented, therefore, by two sides of a right triangle. The capacity of a circuit causes a charging current which is however of importance only at the higher voltages. See Sec. 11.

The inductive reactance of a circuit is ωL, where $\omega = 2\pi n$ and n = frequency in cycles per second; L = inductance in henrys. The inductance is a measure of the number of lines of force per ampere linked with the circuit; it increases, therefore, as the separation of the conductors of the circuit is increased, or with the introduction of iron into the magnetic field, since either of these increases the number of lines of force linked with the circuit.

29. Table of wire resistance and reactance. The table in Par. 21 gives the reactance drop in volts per ampere, for 1,000 ft. of conductor, for the distances of separation and sizes of wire commonly used in transmission and distribution work. It should be noted that the *reactance increases as the separation is increased.*

30. Example of calculation of resistance and reactance drops. A single-phase circuit 10,000 ft. long operates at 60 cycles and carries a load of 100 amp., with No. 0 wires 12 in. apart. What are the values of the inductive and the ohmic components of drop, and the impedance drop? The reactance per 1,000 ft., per amp. per wire, for No. 0 wires 12 in. apart is $X = 0.1043$. The resistance is 0.098 ohm. per 1,000 ft. The inductive component of the impedance of the circuit is

$$X = 2D \times I \times 0.1043/1{,}000 = 2 \times 10{,}000 \times 100 \times 0.1043/1{,}000 = 208.6 \text{ volts.}$$

The ohmic component is $R = 2 \times 10{,}000 \times 100 \times 0.0981/1{,}000 = 196.2$ volts. The impedance drop in the circuit is

$$\sqrt{(209)^2 + (196)^2} = 286 \text{ volts.}$$

The length of the line OA in Fig. 9 is proportional to the resistance component, that of AB represents the inductive component and OB the resultant of the two. If the circuit consisted of two No. 6 wires the resistance component would be 788 volts, the inductive component 241 volts, and the impedance drop would be

$$\sqrt{(788)^2 + (241)^2} = 824 \text{ volts.}$$

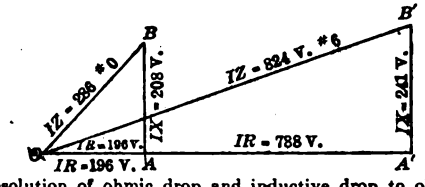


FIG. 9.—Resolution of ohmic drop and inductive drop to obtain total or impedance drop.

The e.m.f. diagram for the latter case, in Fig. 9, is $OA'B'$. It is apparent that the ratio of resistance to inductance decreases as the size of wire is increased, so that increasing the size for the purpose of reducing the pressure-drop becomes less effective in the larger sizes. It is preferable to install an additional circuit if facilities will permit.

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31. Table of Resistance Drop and Reactance Drop in Volts per Amp., per 1,000 ft., per Wire, at 60 Cycles

Size in cir. mils or A.W.G.	Lb. per 1,000 ft. bare.	Lb. per 1,000 ft. T. B. weatherproof.	Resistance, ohms per 1,000 ft. at 68 deg. fahr.	Volts drop per amp. per 1,000 ft. of (one) wire at 60 cycles										
				Distance between centres										
				½ in.	1 in.	2 in.	3 in.	6 in.	12 in.	18 in.	24 in.	36 in.	48 in.	60 in.
1,000,000	3,050	3,610	0.01035	.....	.....	.....	.....	0.063	0.0784	0.0877	0.0943	0.1036	0.1102	0.1153
500,000	1,525	1,870	0.0207	.....	.....	.....	.....	0.071	0.0864	0.0957	0.1023	0.1116	0.1182	0.1233
350,000	1,068	1,320	0.0296	.....	.....	.....	.....	0.0746	0.0905	0.0998	0.1064	0.1157	0.1223	0.1274
0000	640.5	754	0.0489	0.0328	0.0394	0.0553	0.0646	0.0805	0.0964	0.1057	0.1123	0.1216	0.1282	0.1333
000	508	614	0.0617	0.0355	0.0421	0.058	0.067	0.0832	0.0991	0.1084	0.1150	0.1242	0.1308	0.1360
00	402.8	486	0.0778	0.0381	0.0447	0.060	0.070	0.0858	0.1017	0.1110	0.1176	0.1269	0.1335	0.1386
0	319.5	388	0.0981	0.0408	0.0474	0.0633	0.0726	0.0885	0.1043	0.1136	0.1202	0.1295	0.1361	0.1412
1	253.3	312	0.1237	0.0435	0.0501	0.0659	0.0752	0.0911	0.1070	0.1163	0.1229	0.1322	0.1388	0.1439
2	200.9	254	0.156	0.0461	0.0527	0.0686	0.0779	0.0938	0.1097	0.1190	0.1256	0.1348	0.1414	0.1466
4	126.4	163	0.248	0.0514	0.0580	0.0739	0.0832	0.0991	0.1150	0.1243	0.1309	0.1402	0.1468	0.1519
6	79.46	112	0.394	0.0567	0.0633	0.0792	0.0885	0.1044	0.1203	0.1296	0.1362	0.1455	0.1521	0.1572
8	49.98	73.8	0.627	0.0621	0.0687	0.0845	0.0938	0.1097	0.1256	0.1349	0.1415	0.1508	0.1574	0.1625
10	31.43	50.2	0.997	0.0674	0.074	0.0898	0.0991	0.1151	0.1309	0.1402	0.1468	0.1561	0.1627	0.1678

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32. Resistance and inductance factors. The **resistance factor** of a circuit is the ratio of its resistance to its impedance. Likewise the **inductance factor** is the ratio of the inductive reactance to the impedance. The square root of the sum of the squares of these two factors is equal to unity. The values of inductance factor which correspond to various common values of resistance (or power) factor appear in the following table:

Resistance (or power) factor, per cent.....	50	60	65	70	75	80	85	90	95	97.5	100
Inductance factor, per cent.....	86.6	80	76	71	66	60	53	44	31	22.2	0

33. Single-phase line drop. In an alternating-current circuit the pressure-drop is determined from the resistance and the inductance components in conjunction with the power-factor of the load which the circuit is carrying. The line drop is a maximum when the power-factor of the load equals the resistance factor of the line.

Referring to Fig. 10, the line *OE* represents the pressure delivered. *OR* is the component of *OE*, which is doing useful work; *ER* is the component of self-induction, or inductive component, which causes the current to be out of phase with the impressed voltage at the load. *EL* is the resistance component of the line drop, and *LP* is the inductive component. The resistance component of the line drop, *EL*, and the power component of the impressed load voltage, *OR*, are in phase with each other; and the inductive components *ER* and *LP* are in phase. The resultant *OP* is the bus pressure, or impressed line voltage, necessary to deliver a pressure *OE* at the end of the line. The net line drop is the numerical difference between *OP* and *OE*. In the case of non-inductive load, such as incandescent lamps, the inductive component *ER* disappears, and the impressed voltage at the lamps takes the position of *OF* (=*OE*). The impressed line pressure necessary to deliver *OF* at the lamps is *ON*, or the resultant of *OM* (=*OF*+*EL*) and *MN* (=*LP*), and the drop is the numerical difference between *ON* and *OF*.

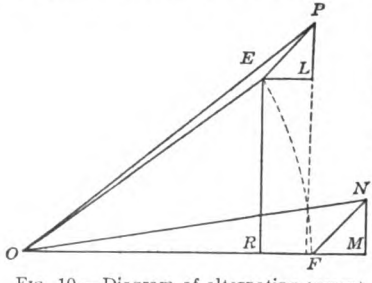


FIG. 10.—Diagram of alternating-current line-drop under inductive load.

34. Example of calculation of single-phase line drop. Given a load of 100 amp. of 2,200 volts, single-phase, delivered at the end of a two-wire line of No. 0 copper wire, 4,500 ft. long, with wires 12 in. apart, a frequency of 60 cycles and a power-factor of 80 per cent., what is the line drop?

The power-factor being 80 per cent., the corresponding inductance factor is 60 per cent., from the table in Par. **32**. Using the notation of Fig. 10:

$$OR = 0.80 \times 2{,}200 = 1{,}760 \text{ volts.}$$
$$ER = 0.6 \times 2{,}200 = 1{,}320 \text{ volts.}$$

The line resistance drop per 1,000 ft., per ampere, for No. 0 wire (Par. **31**) is 0.098 volt. Hence the total line resistance drop is

$$EL = 2 \times 0.0981 \times 4.5 \times 100 = 88 \text{ volts.}$$

The line inductive drop per 1,000 ft., per ampere, for 12-in. centres, is 0.104 volt, and therefore

$$LP = 2 \times 0.1043 \times 4.5 \times 100 = 94 \text{ volts.}$$

The total power (resistance) component is $OR+EL$, or $1{,}760+88=1{,}848$ volts, and the total inductive component is $ER+LP$, or $1{,}320+94=1{,}414$ volts. The resultant of these two is

$$OP = \sqrt{(1{,}848)^2+(1{,}414)^2} = 2{,}327 \text{ volts.}$$

This is the pressure necessary to deliver 2,200 volts at the end of the line.

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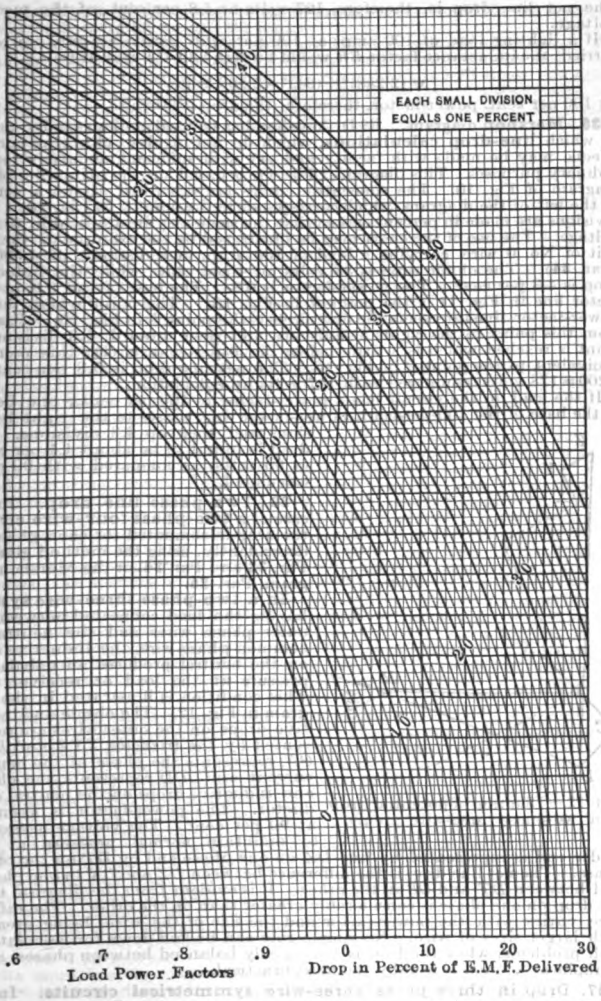


FIG. 11.—Mershon chart for calculating drop in alternating-current lines.

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The net line drop is, therefore, 127 volts or 5.8 per cent. of the receiver voltage.

If a lighting load of 100 amp. at 100 per cent. power-factor were being carried, the inductance factor ER would be zero and ON would be

$$\sqrt{(2{,}288)^2+(94)^2}=2{,}290 \text{ volts.}$$

At 100 per cent. power-factor, therefore, the drop is 90 volts.

35. Mershon diagram. R. D. Mershon has devised a diagram by means of which **line-drop calculations,** which do not involve charging-current effects, may be made with facility and yet with sufficient accuracy for all ordinary purposes. This diagram,* Fig. 11, is based on the principles of the diagram of Fig. 10. The concentric circles are described about a centre, to the left of the diagram, which corresponds to the point O in Fig. 10. The divisions are made in percentages so that the scale may be applicable to any voltage. The use of the chart may be illustrated by the example of the circuit of No. 0 wire carrying a load of 100 amp. at a distance of 4,500 ft. (Par. **34**). The ohmic drop is 88 volts, or 4 per cent., while the inductive drop is 4.3 per cent. The power-factor is 0.8. The base of the 0.8 power-factor line in Fig. 11 is the point R in Fig. 10. The point where the 0.8 power-factor line intersects the first circle is the point E in Fig. 10. Passing from this point to the right, 4 divisions, and then upward, 4.3 divisions, a point is reached which is a little below the 6-per-cent. circle; this point is equivalent to the point P in Fig. 10. The net line drop is 5.8 per cent. of 2,200 = 128 volts, compared with 127 volts by calculation.

If the load on the circuit has a power-factor of 100 per cent., one begins at the base of the 100-per-cent. power-factor line, passes to the right 4 divisions and then up 4.3 divisions. The drop is found to be about 4.1 per cent., or 90 volts, as compared with 90 volts calculated.

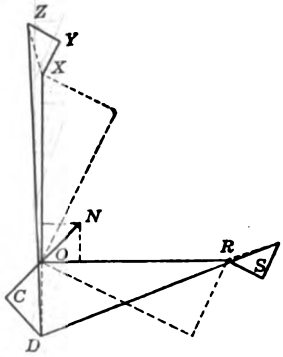


FIG. 12.—Diagram of potential drop on two-phase three-wire circuit.

36. Two-phase line drop. In the case of a **two-phase four-wire circuit** the drop is computed for each phase independently, using the method given in Par. **33** and Par. **34**, or the Mershon diagram, Par. **35**.

In a two-phase three-wire system having the load connected between the outer phase wires and the neutral or common phase wire, the inductive drop on the neutral produces an unbalanced pressure at the load or receiver end. This condition is illustrated in the diagram in Fig. 12. The ohmic and inductive drops on the outer wires are represented by the triangles XYZ and RST. ON represents the phase of the neutral current and OCD represents the ohmic and inductive drops on the neutral conductor. The power-factor is assumed at 90 per cent. The voltage necessary to maintain normal pressure at the feeder end is represented by line DZ on one phase and by DT on the other phase. The net line drop is the difference between DZ and OX in one phase, and between DT and OR in the other. It is evident from the diagram that the drop on one phase is considerably greater than on the other. The difference varies with the power-factor and the size of the wire, being greater with larger sizes of wire. No simple rule can be laid down for calculating such problems, when the load is not equally balanced between phases, and a graphical solution is usually the most practical.

37. Drop in three-phase three-wire symmetrical circuits. In a three-phase three-wire circuit with conductors symmetrically arranged and carrying a balanced load, the inductive effect is the same in each wire and

* *American Electrician*, June, 1897.

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the calculation of drop may be made exactly as it would be for a single-phase circuit carrying one-half the load.

As the currents in the three wires are 120 deg. apart in time phase, the ohmic drop for the two wires making up any one phase is not twice that of one wire, as it is in a single-phase two-wire circuit, but is 1.73 times this drop. The inductive component of drop is also 1.73 times that of a single wire, for the loop. If the load on a three-phase circuit were the same as on the single-phase circuit in the previous example (Par. 34), the current per wire in the three-phase circuit would be

$$\frac{100 \times 1.732}{3} = 57.7 \text{ amp.}$$

The drop at 100 amp. on the three-phase circuit would be $(5.8/2) \times 1.73 = 5.0$ per cent., and at 58 amp. the drop would be 58/100 of 5 per cent., or 2.9 per cent. The single-phase drop at the same load was found to be 5.8 per cent., or twice the three-phase drop.

Therefore, for the same load and equal line drop, the size of the conductor in a three-phase circuit may be one-half that of a single-phase circuit. There being three wires in the three-phase circuit, it follows that the *weight of copper which is required for a three-phase circuit is three-quarters of that required for single-phase* transmission, with equal pressures between phase-wires, equal loads and equal line drops.

38. Drop in three-phase three-wire unsymmetrical circuits. When the arrangement of conductors is not symmetrical, the inductive component of drop is different among the different pairs of wires, on account of the different distances between centres. The most common case is that in which the wires are arranged on a cross-arm in the same horizontal plane. In such cases the equivalent of a symmetrical arrangement can be secured by transposing the conductors at proper intervals. This is not necessary in 2,200-volt distributing feeders which are equipped with line-drop compensators, as they can easily be adjusted to correct the unbalanced conditions.

The calculation of drop in an unbalanced three-wire three-phase circuit is somewhat complicated and such problems are most readily solved graphically. Loads which are not unbalanced more than 10 per cent. to 15 per cent. may usually be averaged and considered as balanced for practical purposes. In systems where the lighting service is all on one phase, and the third phase wire carries a small scattered load of three-phase motors, the lighting phase may be considered as a single-phase circuit in computing the drop. However, as the motor load increases, the drop in the lighting phase becomes less for a given current value, until, when the current in the other phases equals that in the lighting phase, the drop in the latter is but 86.6 per cent. of what it would be with the same current carried for lighting service only.

39. Drop in three-phase four-wire circuits. The pressure at the transformer, on such systems, is the pressure between phase wires and neutral; when the latter is 2,200 volts, the pressure across phase wires is $2,200 \times 1.732 = 3,810$ volts. With **balanced load** the neutral conductor carries no current and the drop is that in the phase wires only. The resistance drop at 100 amp. on a No. 0 circuit 9,000 ft. long is $100 \times 9 \times 0.0981 = 88$ volts. This is 4 per cent. of 2,200 volts. Assuming a 12-in. spacing, single-phase, the inductive component of drop is $100 \times 9 \times 0.1043 = 94$ volts, or 4.3 per cent. At 80 per cent. power-factor, by the Mershon diagram (Fig. 11), the total drop is 5.8 per cent. The size of wire for a given load and drop, three-phase, is one-half what it would be for a single-phase circuit, or, assuming wires of equal size, the distance may be doubled for the same drop as compared with a single-phase circuit.

In the case of an **unbalanced four-wire circuit**, which is the more usual condition, the effect of the drop on the neutral wire must be taken into consideration. In general, the effect of the unbalance is to increase the drop on the more heavily loaded phases and decrease it on the lightly loaded phases, in comparison with the drops at balanced load, as shown in the case of the three-wire two-phase circuit above. A graphical solution of the problem of determining line drop in unbalanced three-phase four-wire circuits is shown in Fig. 13. This diagram is constructed on a principle similar to that used in Fig. 12 for a two-phase circuit.

The load on A phase is heavier than that on B and C, and the drop OE due

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to the neutral current is added almost directly to the drop *XZ* on the *A*-phase conductor.

The net drop on *A* phase is *EZ–OX*, that on *B* phase is *ET–OR* and on *I* phase it is *EW–OU*.

Where line-drop compensators are employed in each conductor, only the individual calculations for the four conductors are required, as the compensator corrects for the effect of the neutral drop.

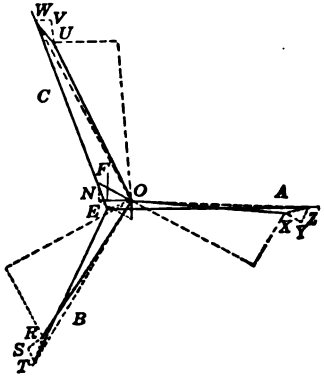


FIG. 13.—Diagram of drops in a three-phase four-wire circuit.

40. Skin effect is an alternating-current phenomenon (Sec. 2, and Sec. 4), which materially affects cables of large cross-section, due to the fact that the currents passing through the strands around the outer surface of the cable encounter less inductance and impedance than the strands near the centre, thus causing the outer strands to carry more current, proportionately, than the inner strands. It is desirable, therefore, to build up large cables about a core of non-conducting material. Cables of over 500,000 cir. mils are often made in this manner where they are to be used in 60-cycle systems, and cables of more than 1,000,000 cir. mils for 25-cycle systems.

The increase in effective resistance due to skin effect is approximately proportional to the product of the frequency and the circular mils, as shown in the following table in Par. 41.

41. Table of Skin-effect Coefficients

Cir. mils × frequency	Coefficient	
	Copper	Aluminum
10,000,000	1.000	1.000
20,000,000	1.008	1.000
30,000,000	1.025	1.006
40,000,000	1.045	1.015
50,000,000	1.07	1.026
60,000,000	1.096	1.04
70,000,000	1.126	1.053
80,000,000	1.158	1.069
90,000,000	1.195	1.085
100,000,000	1.23	1.104
125,000,000	1.332	1.151
150,000,000	1.433	1.206
175,000,000	1.53	1.266
200,000,000	1.622	1.33

To determine the skin effect of a copper cable having an area of 1,000,000 cir. mils, carrying current at 60 cycles, refer to the table, opposite the product 60,000,000. The coefficient is 1.096. The resistance of a 1,000,000-cir. mils cable per 1,000 ft. being 0.01035, the effective resistance at 60 cycles is $0.01035 \times 1.096 = 0.01134$, or 9.6 per cent. more than with continuous current. The resistance of a 1,500,000-cir. mils cable is increased 19.5 per cent. at 60 cycles. The current-carrying capacity of large cables is reduced in proportion to the reciprocal of the skin-effect coefficient; that is, if the coefficient is 1.096, the capacity is only $1/1.096 = 91.2$ per cent. of that with continuous currents.

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43. Effect of electrostatic capacity. At ordinary distributing voltages and frequencies the capacity effect is too small to be of any consequence in the solution of line-drop problems and need not be considered. At the higher transmission voltages it is a matter of considerable importance in many cases (Sec. 11). The electrostatic capacity of an overhead circuit is fixed by the distance between the conductors and by their size; with insulated conductors (aerial or in cable), the capacity is further affected by the dielectric constant (Sec. 4), of the insulating material. The mutual capacity of a single-phase uninsulated circuit strung in the open air, per 1,000 ft. of circuit, is given by

$$C = \frac{0.003677}{\log \frac{d}{r}} \quad \text{(microfarads)} \qquad (2)$$

where d is the distance between centres of conductors and r is half the diameter (radius) of the conductor. The logarithm used is the *common logarithm*.

43. Charging current. The charging current of a single-phase circuit is given by

$$I = \frac{6.284DnCE}{1{,}000{,}000} \quad \text{(amp.)} \qquad (3)$$

where D is the length of circuit in thousands of feet, n is the frequency, C is the capacity in microfarads, and E is the effective voltage between conductors. The charging current of a symmetrical three-phase circuit, between phase wires, is $2/\sqrt{3} = 1.155$ times that of a single-phase circuit with equal spacing between phase wires.

When an inductive load is carried on the line, the lagging component of the load current tends to offset the leading current required to charge the line. The tendency of the charging current to raise the power-factor of the line current thus results in a corresponding tendency to reduce the line drop where the load is of an inductive character. (For full treatment of the effect of capacity on line drop, see Sec. 11.)

44. Electrostatic capacity of cables. In underground cable work the effect of charging current is greatly increased by the reduced separation of the conductors. The charging current cannot be determined by direct calculation, however, since the dielectric constant of the insulation must be taken into account. The mutual capacity of a three-phase three-conductor cable between conductors, per 1,000 ft., is given by

$$C = \frac{0.00735\ K}{\log \frac{3a^2\ (R^2 - a^2)^3}{r^2\ (R^6 - a^6)}} \quad \text{(microfarads)} \qquad (4)$$

When K is the dielectric constant, a is the distance from the centre of the cross-section of the cable to the centre of the conductors, R is the radius of the inside of the lead sheath, and r is the radius of the conductors. The *common logarithm* should be used.

45. Dielectric constant. The value of K, the dielectric constant, varies with the character of the paper and oils used and increases as the temperature increases. It must therefore be determined for each cable by measurement at the various temperatures of operation. The charging current is also affected by the dielectric loss in the cable insulation, and with cables designed for operation at voltages above 13,200, this becomes an important factor since it tends to reduce the current-carrying capacity of the cable by adding heat, which contributes to the temperature rise. Also see Par. 48.

46. Current-carrying capacity of conductors. The energy absorbed by a circuit, I^2R, is dissipated in the form of heat, and tends to raise the temperature of the conductor. The maximum current-carrying capacity of a conductor is dependent upon whether it is installed in open air, in conduit or underground. The character of the insulation is also a factor, since certain kinds of insulation may be safely operated at higher temperatures than others.

The insulation of rubber-covered conductors should not be operated regularly at temperatures above about 50 deg. cent. (122 deg. fahr.). Weatherproof and other fibrous types of insulation may be operated at temperatures as high as 65 deg. to 70 deg. cent. (149 deg. to 158 deg. fahr.). Conductors used inside of buildings are subject to the requirements of the National

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Electrical Code, which limits the current in rubber-covered cables to values such that the temperature rise will not exceed about 15 deg. cent. (27 deg. fahr.). This represents a temperature of about 40 deg. cent. (104 deg. fahr.) during summer months, or in parts of buildings such as engine rooms which are normally above outside air temperature. Slow-burning insulation is accordingly required in places where the temperature is likely to be above 45 deg. cent. (113 deg. fahr.).

47. Table of Current-carrying Capacity of Wires and Cables Under Various Conditions

Size, A.W.G. or cir. mils	National electrical code		Lead-covered cables		
			Single conductor		Three conductor paper ins. 45 deg. cent. rise. (amp.)
	Rubber ins. (amp.)	Slow-burning ins. (amp.)	Rubber 30 deg. cent. rise (amp.)	Paper or cambric, 40 deg. cent. rise (amp.)	
14	15	20	.....	.....	.....
12	20	25	.....	.....	.....
10	25	30	20	22	.....
8	35	50	30	34	26
6	50	70	50	56	48
4	70	90	78	87	68
3	80	100	98	110	81
2	90	125	121	134	93
1	100	150	145	160	110
0	125	200	169	187	132
00	150	225	192	210	150
000	175	275	245	270	190
0000	225	325	285	315	225
250,000	235	350	320	360	255
300,000	275	400	370	415	300
400,000	325	500	460	515	370
500,000	400	600	550	605	.....
750,000	525	800	750	830	.....
1,000,000	650	1,000	900	1,030	.....
1,500,000	850	1,360	1,200	1,450	.....
2,000,000	1,050	1,670	1,400	1,590	.....

48. Underground cables. The carrying capacity of lead-covered cables in underground conduit has been studied by various investigators but no complete study has been made of the various factors involved. The radiation from a duct line varies with the character of the soil, size and shape of duct line and with the presence of other heat producing elements such as steam heating mains and other conduit lines. The radiation from the cables in the inside ducts is materially less than from those in the peripheral ducts, a difference of 15 per cent. having been noted by Fisher in a 9-duct line and 40 per cent. in a 16-duct line when all ducts are occupied by loaded cables.

With oiled paper cables the maximum temperature is limited, by the Standardization Rules of the A. I. E. E., to $85-E$ deg. cent., where E is the pressure in kilovolts.

This limit is fixed as a basis of continuous operation, but low-tension direct-current cables have been operated at temperatures of 100 to 120 deg. cent. for several hundred hours without showing perceptible damage.

With high-tension cables the limit should not be exceeded materially since the dielectric loss increases with the temperature and adds to the heat generated as the temperature increases. At voltages above 10,000 the dielectric loss may be sufficient to reduce the carrying capacity of the cable. Attention has been given in recent years to the compounds used in such cables, and it is found that the use of resin oil, the predominant element being made up of mineral compounds, should be limited if the dielectric loss is

Atkinson and Fisher. *Trans.* A. I. E. E.; Vol. XXXII, 1913, p. 327.

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to be kept within safe limits. The tendency of the loss to increase as the temperature rises produces a condition of cumulative heating which may progress in a few hours to a point where the cable is destroyed.

49. Temperature of conductors. The temperature of the conductor may be determined from observation of the temperature of the cable sheath by a formula derived by Atkinson and Fisher, which is of value since it can be easily applied to working cables, without taking them out of service. The fall of temperature from conductor to sheath is

$$t = K \log \left(\frac{D}{d}\right) \left(\frac{I^2 \times 1{,}000}{\text{cir. mils}}\right) \text{(deg. cent.)} \qquad (5)$$

in which D is the diameter (in.), outside the insulation, d is the diameter (in.) of the conductor, I is the current (amp.) and K is a constant which is determined for each type of cable. The common logarithm, base 10, should be used. The values of K are as follows: for single conductor cable, 0.15; for two-conductor cable, 0.35; and for three-conductor cable, 0.52.

With multiple conductor cable the value of D is taken over the outer belt of insulation and d is that of the individual conductors.

50. Multiple conductor cables. The carrying capacity of multiple conductor cables is less than that of single conductor cables of the same size of conductor, since heat is generated in two or more conductors and the increase in radiating surface is not proportionally greater. This effect is such that for duplex cable the temperature rise is about 10 per cent. greater than for a single conductor cable, making its carrying capacity about 10 per cent. less. For three-conductor cable the carrying capacity is about 75 per cent. of that of a single conductor cable.

SUBSTATIONS

51. The function of a substation is to convert energy received from a bulk-supply system, at the transmission voltage and frequency, to energy suitable for distributing purposes. The energy distributed may be in the form of direct current at the voltage at which it is utilized, or in the form of alternating current at a voltage suitable for general distribution through step-down transformers located at suitable points in the district served. The expense of installing and operating a substation must be justified by the saving made by the shortening of distributing feeders and the reduction in feeder losses incident thereto.

52. Substation location. The distance between substations depends upon the voltage of distribution and the density of the load. The average length of the distributing feeders should be such that the total investment in feeder conductors and substation equipment is a minimum.

In low-tension systems it is usually found desirable to locate substations approximately 1 mile apart, except in very congested districts where they are sometimes located less than 0.5 mile apart, on account of the very large loads to be carried.

In 2300-volt alternating-current distribution, substations may be spaced from 2 to 3 miles; in four-wire systems operating at 2,300–4,000 volts, they may be located from 4 to 6 miles apart, in scattered districts. In the outlying parts of the larger cities they are usually found from 2 to 3 miles apart on account of the density of the load.

53. Substation classification. Substations may be divided into three principal classes: (a) those in which transformers change the pressure from that used in transmission to the distribution voltage; (b) those in which frequency changers convert energy from one frequency to another and from the transmission voltage to the distributing voltage; and (c) those in which the transmitted energy is converted by synchronous converters to continuous current at low voltage.

54. General features. Each of these classes of substations (Par. **53**) has certain elements which are common to all. Each is served by incoming transmission lines which are terminated in oil switches and connected thence to a high-tension bus system. One side of the converting apparatus is connected to the high-tension bus and the other side to two or more distributing busses. From these busses the outgoing feeders are taken off through suitable feeder switches, in conjunction with regulating apparatus.

55. Substation building. The size of the lot and the dimensions of the building should be such as to permit an arrangement of apparatus which will not be unduly crowded, and which will permit the installation,

* Fisher, H. W. *Trans.* A. I. E. E.; Vol. XXII, 1903, p. 440.

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repair and maintenance of the equipment at minimum cost. Where further growth is probable, due regard must be had for subsequent extensions of building and equipment. Fireproof construction is warranted where continuous service is important.

56. Bus-bar arrangement. Fig. 14 shows a simple arrangement for a substation having one main line and one reserve line. Where the load is such that several direct lines are required, a **transfer bus** (Fig. 15) is very desirable. This permits the operation of any machine from any line and makes the reserve line available in case of the failure of any of the main lines.

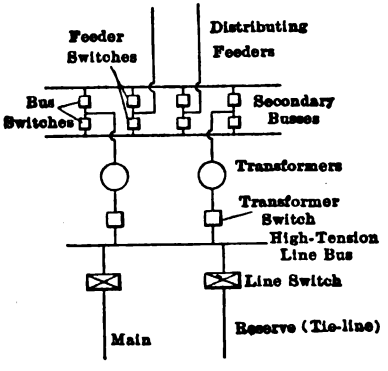


FIG. 14.—High-tension bus arrangement in a small substation.

57. Duplicate distributing busses are provided both as a means of operating the longer feeders at a higher bus pressure, and as a means of facilitating repair and maintenance work without interrupting service.

58. In continuous-current systems, two busses are required in practically all cases for **pressure control** during the heavy-load period, and in the larger substations it is sometimes necessary to provide **three busses** to take care of certain feeders which are exceptionally long or very short.

59. Transformer substations. The simplest type of substation is that which transforms alternating-current energy from one voltage to another

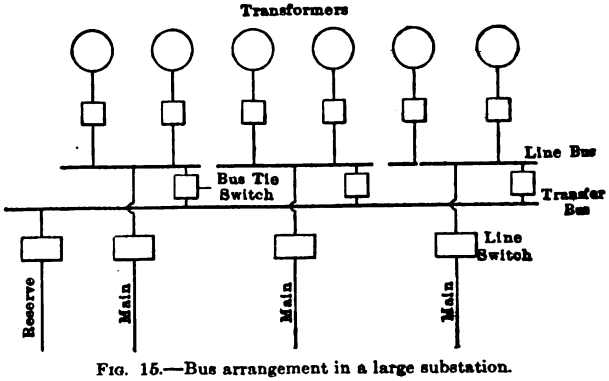


FIG. 15.—Bus arrangement in a large substation.

and requires, therefore, only transformers for the converting equipment. Both oil-cooled and air-cooled types of transformers are used for this purpose, with either single-phase or three-phase units. Oil-cooled units are preferable where the substation may be left without attendance during certain hours

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of the day. Oil-insulated, water-cooled transformers are used quite generally where there is an ample supply of cooling water.

Single-phase units are commonly employed where capacities of less than 1,000 kw. are required, although there is no settled practice in this regard.

Three-phase units are less expensive than single-phase units, particularly in the larger sizes, and require considerably less floor space.

60. Frequency-changer substations. Where the transmitted energy is converted to another frequency, the equipment consists of a motor generator, usually of the synchronous type; the motor is usually wound for the transmission voltage, to avoid the investment in transformers, where the voltage is less than 15,000 volts. This type of apparatus requires an exciter equipment, which may be driven by the machine itself, or by a separate motor. There should be at least one separately driven exciter equipment in a station where the exciters are direct connected.

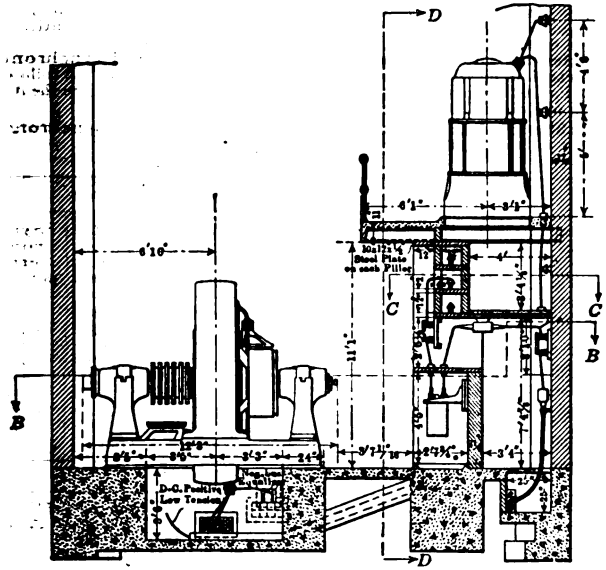


FIG. 16.—Synchronous converter substation.

61. The synchronising equipment of frequency-changer sets must be so arranged that synchronising can be done at both frequencies. When the machine is brought into step on the transmission side, the arrangement of the poles is such that the generator end is held with a fixed angle of phase displacement from the supply system, except for one particular (and correct) position of the motor fields. In a 25-cycle to 60-cycle frequency changer having ten and twenty-four poles respectively, there are *five* positions in which the 25-cycle machine may come into synchronism, only *one* of which will permit the 60-cycle (generator) end to be synchronised with another frequency changer already in operation. The 60-cycle end must be synchronised by slipping poles until it comes into phase. Where the frequency changer is being synchronised with a generating system, it is necessary to advance or retard the phase of the 60-cycle generators.

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63. Continuous-current substations. A continuous-current suppl is usually derived from transmission systems by the use of synchronous con verters, or motor-generators. The synchronous converter is universall employed where the transmission system is operated at 25 cycles, as th converter is less expensive in first cost and more efficient in operation than motor-generator. Converters have been little used in 60-cycle systems unt recent years. The development of the interpole converter has minimise the tendency of 60-cycle converters to hunt and flash over.

Where motor-generators are employed both synchronous and indu tion types of motors are in use. The induction motor has the advanta of greater stability than the synchronous motor in times of disturbance t the frequency or the voltage of the system. The induction motor, hov ever, has a power-factor (lagging) of about 85 per cent., whereas the syn chronous motor has an adjustable field and may be operated (overexcited with a leading power-factor, thus raising the power-factor of the generatin system. It has become customary, therefore, to employ both synchronou and induction types of motors in converting 60-cycle energy to continuou current energy, in order to secure the advantages of both.

Efficiencies and first costs of motor-generators and synchronou converters at one-half, three-quarters, and full load appear in the followin table (Par. **63**), compiled from a paper read by E. W. Allen before the Asso ciation of Edison Illuminating Companies, 1908.

63. Tables of Efficiencies, Cost and Floor Space of Synchronou Converters and Motor-generators

Efficiencies

Rating, kw.	Per cent. load	25 cycles			60 cycles		
		Syn. mot.-gen. per cent.	Ind. mot.-gen., per cent.	Syn. con-verter, per cent.	Syn. mot.-gen., per cent.	Ind. mot.-gen., per cent.	Syn. con-verter, per cent.
300	100	84	85.3	89.5	86.7	84.8	88
300	75	82.3	83.3	88.5	85	82.3	86.7
300	50	77	79.8	86.5	81.7	79	82.5
500	100	85.5	86.8	90.8	87.8	86.3	89
500	75	83.7	84.8	90.3	86	84.3	87
500	50	79.5	82	88.3	83	81	83
1000	100	87.5	87	91.8	87.8	87	.....
1000	75	86	85.8	90.5	86	85.3	.....
1000	50	82.2	82.3	90	83	82	.....

Approximate Cost per Kilowatt

300	.....	$26.20	$26.35	$25.15	$25.75	$25.85	$25.00
500	.....	24.70	24.35	22.00	23.20	23.40	22.70
1000	.....	20.25	19.85	19.80	19.45	19.50	.....

Floor Space, Square Feet

300	.....	80	80	91	67	67	96
500	.....	122	122	131	110	110	150
1000	.....	136	136	170	140	140	.....

64. Motor-generator sets are commonly wound for the transmission voltage, and are started by the use of a compensator at fractional voltage. A single compensator is sufficient for a substation if a starting bus is provided through which the same compensator can be used to start any of the units; a spare compensator should be in reserve.

65. The synchronous-converter substation, Fig. 16, is provided with transformers stepping down to the proper voltage for the alternating-current side of the converter. The transformers are commonly of the air-blast, three-phase type, as this form of equipment can be placed in a minimum of space.

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66. Connection of neutral for three-wire continuous-current system.—The six-phase type of converter, wound for 250 volts, with a diametrical connection in order to provide for the neutral conductor, Fig. 17, is commonly employed for machines of 1,000 kw. and larger. Motor-generators are also designed for 250 volts, a small **balancer-set** being used to take care of the unbalanced load.

67. The regulation of pressure on the bus supplied by a synchronous converter is accomplished by the use of an induction regulator placed between the transformers and the converter. Some variation in pressure can be secured by manipulation of the converter field-rheostat, but this affects the power-factor and it is not depended upon for pressure control.

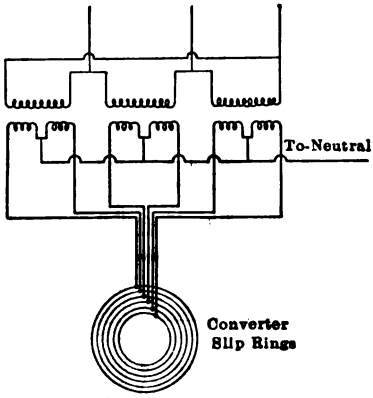


FIG. 17.—Six-phase diametrical connection for synchronous converter.

68. In the split-pole type of converter, which has been introduced in recent years, considerable range of **pressure regulation may be secured** by variation of the field rheostat without serious interference with the power-factor, and with this type of machine regulators are sometimes omitted.

69. Synchronous converters may be started in various ways, and it is usual to provide for at least one method of starting from both the alternating-current and the continuous-current sides. The converter may be started from the continuous-current side by the use of a starting rheostat in practically the same manner as that used in starting a continuous-current motor.

The converter may be started from the alternating-current side with the field open, by impressing approximately half the normal pressure, derived from a starting compensator or half-taps on the secondary of the transformer. The latter method is usually preferable. After the machine has come up to speed, the fields are excited and the polarity corrected, if necessary, by reversing the field, and slipping back one pole.

The current required in starting from the alternating-current side is from one and one-half to twice full-load current, while 25 per cent. to 30 per cent. of full-load current is sufficient for starting from the continuous-current side. The normal method of starting is, therefore, preferably from the continuous-current side.

70. Low-tension switchboards. The operation of distributing systems at low pressure involves very large currents and for that reason the most important part of a low-tension switchboard is the arrangement of heavy bars of copper, 3 in. to 6 in. wide and 0.25 in. to 0.5 in. thick, required for the safe handling of such currents. The important features of the design are to maintain sufficient clearance between bars of opposite polarity and to make the connections as short as possible consistent with accessibility for repair and maintenance work.

71. Feeder panels. The switchboard shown in Fig. 18 is based upon a vertical arrangement which permits ample separation of opposite polarities and minimum length of the bus-bar copper per feeder. Each vertical section comprises a set of switches and instruments for one three-wire feeder, the neutral not being brought into the main board. The neutrals are commonly carried to a separate bus in the basement, where they are connected without disconnecting switches other than removable copper links.

72. Switchboard voltmeters. It is customary to provide a single voltmeter with a multiple-point switch so arranged that one voltmeter can

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be used to take the pressure readings on the pressure wires of any of the feeders. Separate voltmeters are provided to give continuous indications of the pressure on each bus.

73. Switchboard ammeters are provided in each side of outgoing feeders in order to give an indication of any excessive unbalance of the load. These are also required for each machine.

74. Number of sets of busses. **Two sets** are commonly required for proper distribution, one bus being operated at a higher pressure than the other. In the large substations it is sometimes desirable to operate as many as three busses.

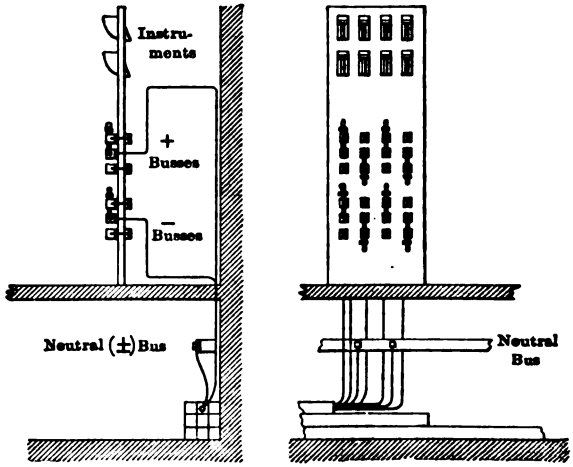


FIG. 18.—Low-tension feeder bus.

75. Knife switches. Single-pole, double-throw knife switches are provided for the control of the feeders, each feeder being so arranged that it can be thrown to either of two busses. This permits the longer feeders to be put on a higher-voltage bus at the time of the heavy load, thus maintaining an even pressure throughout the network.

76. Boosters. It is often necessary, in substations near the edge of the system, to maintain booster-sets which can be put in series with extra long feeders in order to maintain pressure at the distant end. Similarly, very short feeders are sometimes provided with resistances (equivalent to negative boost) to absorb part of the pressure. These resistances are made adjustable for two or three values, and must have ample radiating capacity to avoid overheating at full load. Strips of galvanised sheet-iron have been found very satisfactory for this purpose.

77. Storage-battery reserve. One of the principal advantages of continuous-current distribution is the possibility of having a storage-battery reserve. In order to be of the greatest value, the battery reserve should be distributed in a number of individual units located at central points in the system, so that it can act as a reserve in case of the failure of the supply in any part of the system.

78. Battery rooms. On account of the evolution of gases, and the presence of acid vapor, it is necessary that the portion of the building occupied by the battery be provided with ample ventilating facilities and that all metal work be covered or painted as well as possible.

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79. End-cell switches for battery reserve. The tendency of the battery pressure to fall off at the time of discharge is provided for by the use of end-cell switches which are under the control of the operator, so that additional cells can be connected in series in sufficient number to hold the pressure up to the desired value. Normally, the end-cell switches are set so that the battery floats on the system. In any emergency which causes the bus pressure to drop, the battery immediately begins to supply energy, thus tending to maintain the bus pressure. A diagram of a battery, equipped to act as a reserve on two sets of busses, is shown in Fig. 19.

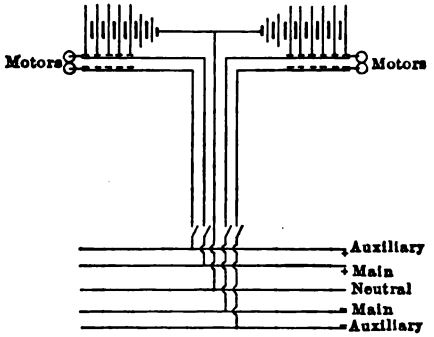


FIG. 19.—Arrangement of battery end-cells.

80. High-tension switchboards (up to 15,000 volts). In the design of high-tension switchboards, the space required for proper separation and insulation of the bus bars, and for the installation of oil-switches, necessitates an arrangement in which the busses and oil-switches are installed in some remote location such as a basement, the control panels being located at a point convenient to the operator.

Ammeters, voltmeters and wattmeters are operated with series (current) and shunt (potential) transformers, and oil-switches are usually of the remote-control type, so that the switchboard panel carries only low-tension apparatus. In smaller substations and in cases where only a few switches are installed, hand control is sometimes employed for the oil-switches on outgoing feeders.

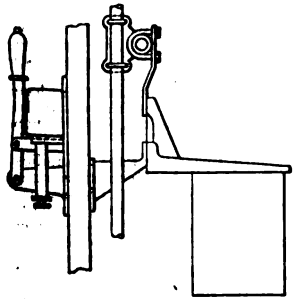


FIG. 20.—Tank-type of oil-switch.

81. High-tension bus bars commonly consist of cable or copper tubing mounted on suitable insulating supports, carried on a skeleton frame of pipe or angle iron. Oil-switches for distributing feeders are commonly mounted on the same framework in such a way as to provide an orderly system of connections from the busses to the switch terminals. Bus bars operating at voltages of 6,600 and upward are commonly installed in compartments, so arranged as to reduce to a minimum the probability of an arc between conductors of opposite polarity; this is very important where large amounts of energy are available to supply a short-circuit in case it should occur.

82. Disconnect-switches should be provided to permit oil-switches to be taken out of service during repair and maintenance work.

83. Two general types of oil-switches are employed, the **tank type** (Par. 84) for distributing-feeders and for the control of converters or transformers, and the **compartment type** (Par. 85) which is used for the control of transmission lines and at other points in the transmission system where the switch may be called upon to open automatically under short-circuit.

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84. The tank type of oil-switch, Fig. 20, is made in single-pole, two-pole, or three-pole construction, with individual tanks which separate the opposite polarities.

85. The compartment type of oil-switch, Fig. 21, is made on a very much larger scale, each pole of the switch being enclosed in a separate compartment of brick or concrete. The front of the compartment is closed by fireproof doors which are hinged at the top to permit heated gases to escape readily, in case they should be liberated in connection with the operation of the switch on a very heavy short-circuit.

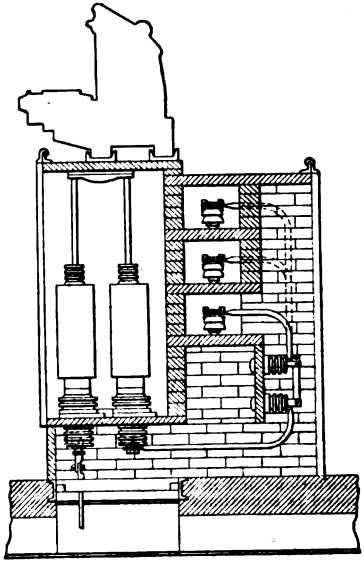


FIG. 21.—Compartment type of oil-switch.

PRESSURE REGULATION

86. Potential regulators. The distributing feeders should be equipped with potential regulators in order to provide proper distribution of pressure. Two types of potential regulators are in general use, one of which consists of a transformer with a switch in the secondary so arranged that approximately 10 per cent. of the bus pressure may be added to, or subtracted from (step by step), the bus pressure. In another type, the secondary of a transformer is mounted on a movable core (Sec. 6), so arranged that more or less of the magnetic flux may be passed through the secondary winding, and the pressure thus raised or lowered by inductive action. The latter is called the **induction regulator** and is preferable to the other type on account of the absence of sliding contacts, which are disposed to be troublesome in operation.

Regulators may be controlled by hand, by motor-drive from hand-operated switches, or by motor-drive from automatically operated switches. The extra expense of automatic control is justified, in important substations, by the improved service given.

87. Line-drop compensators. The use of **pressure wires** to indicate the pressure at the end of a feeder is not necessary on alternating-current feeders, since they can be regulated by the use of line-drop compensators. The length of alternating-current feeders is usually so great that the cost of pressure wires is more than the cost of the compensator equipment. In principle, it consists of a miniature circuit containing the same proportion of resistance and inductance as the feeder circuit which it regulates. The drop in this resistance and inductance is inserted in the voltmeter circuit in such a manner as to reduce the voltmeter reading by the amount of the feeder drop. The amount subtracted from the voltmeter reading the line-drop compensator is directly proportional to the load carried by the circuit and to the power-factor, so that the voltmeter gives a correct indication of the pressure at the feeder-end at all loads, when the line-drop compensator is once properly adjusted.

88. The Westinghouse line-drop compensator, Fig. 22, is designed to provide for a drop of 24 volts with a load of 100 amp. The current from the secondary of the series (current) transformer *S* passes through the induc-

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tive section *B* and the non-inductive section *A* in proportion to the load on the feeder. The secondary winding is divided into four sections of 5 volts each, and four sections of 1 volt each. The 5-volt terminals are connected to the contacts numbered 1, 2, 3, 4, and 5, and the one-volt terminals to the contacts numbered 6, 7, 8, 9, and 10. The arms may be independently adjusted, thus permitting any setting from 1 volt to 24 volts. The current from the shunt (potential) transformer *C* passes through the feeder voltmeter and the two movable arms to 3, thence through the portion of the non-inductive section, which is included between 3 and 5, and the portions of the inductive section between 6 and 9 and between 4 and 5, back to the transformer *C*. In completing this circuit, the impressed pressure has been opposed by a counter-e.m.f. of 10 volts in the non-inductive section and by 8 volts in the inductive section. The reading of the voltmeter is thus made

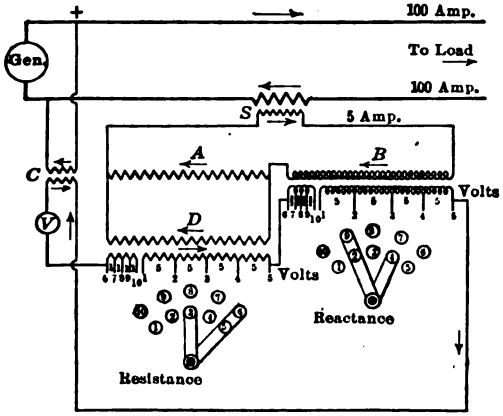


FIG. 22.—Circuits of Westinghouse line-drop compensator.

the same as it would be at the end of a feeder (in the secondary) having a resistance-drop of 10 volts (secondary) and a reactance-drop of 8 volts (secondary) at 100-amp. load.

89. In the General Electric line-drop compensator, Fig. 23, there is but one movable arm on each section, with eight points per section. Each point represents 3 volts when 1 amp. is flowing in the compensator circuit. The compensator shown (Fig. 23) is set so as to introduce in the voltmeter circuit an inductive counter-e.m.f. of 9 volts and a non-inductive counter-e.m.f. of 12 volts, when the feeder is carrying 100 amp.

90. Calculation of compensator setting for a single-phase feeder. Given a 60-cycle feeder of No. 0 A.W.G. copper wire, 5,000 ft. long, single-phase, wires 12 in. apart, series (current) transformer ratio 100 amp. to 5 amp., shunt (potential) transformer ratio 2,200 volts to 110 volts, how should the compensator be set?

The resistance drop on No. 0 wire, from Par. **31**, is 0.0981 volt per amp. per 1,000 ft.; hence the drop at 100 amp., for 5,000 ft., will be $2\times100\times5\times0.0981=98$ volts $=4.5$ per cent. The inductive drop of No. 0, at 12-in. spacing, being 0.1043 volt per amp. per 1,000 ft., the drop at 100 amp. will be $2\times100\times5\times0.1043=104$ volts $=4.7$ per cent. The resistance and the reactance should each be set at 5 volts ($=0.045\times110$), to give constant pressure at the end of the feeder at all loads.

91. Calculation of compensator setting for two-phase feeders. In the case of **a two-phase, four-wire feeder,** the method of connection is

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similar to that used for a single-phase feeder, except that separate equipment is required for each phase, and hence the calculations are similar.

A **two-phase, three-wire feeder**, with unbalanced load requires one compensator in each wire, with connections as shown in Fig. 24. The values of resistance and inductance per 1,000 ft. used in the case of a single-phase feeder are based on the use of two wires, whereas in a three-wire feeder each compensator corrects the drop in one wire only.

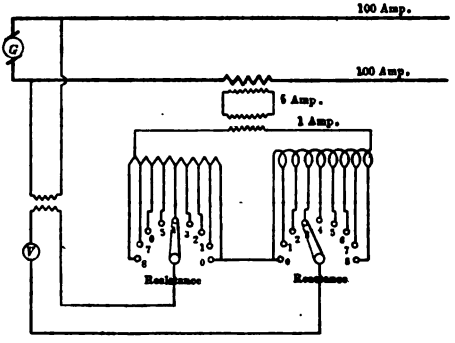


FIG. 23.—Circuits of General Electric line-drop compensator.

92. Calculation of compensator setting for three-phase feeders. In the case of a **three-phase, three-wire feeder** carrying unbalanced load, a compensator is required in each wire. For instance, if the feeder previously used for illustration were a three-phase, three-wire feeder (with symmetrical spacing of phase wires) carrying 100 amp. per wire, the ohmic drop in each wire would be $5 \times 100 \times 0.0981 = 49$ volts, and the inductive drop 52 volts.

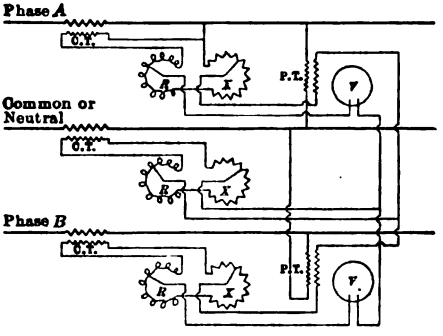


FIG. 24.—Compensator connections for two-phase three-wire system.

These values are respectively 3.8 per cent. and 4.1 per cent. of the pressure to neutral, 1.270 volts ($= 0.577 \times 2{,}200$).

In a **three-phase, four-wire feeder** operating at 2,200 volts between phase wires and neutral, the method of calculating the drop is as follows: Given a feeder of four No. 0 wires (12-in. spacing) running 5,000 ft. from the station as a three-phase feeder, the drop in each phase wire at 100 amp.

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will be 49 volts, ohmic, and 52 volts, inductive. The working pressure being 2,200 volts, this is about 2.5 per cent. If the entire load of the feeder is delivered from this centre of distribution, the compensator on each phase wire

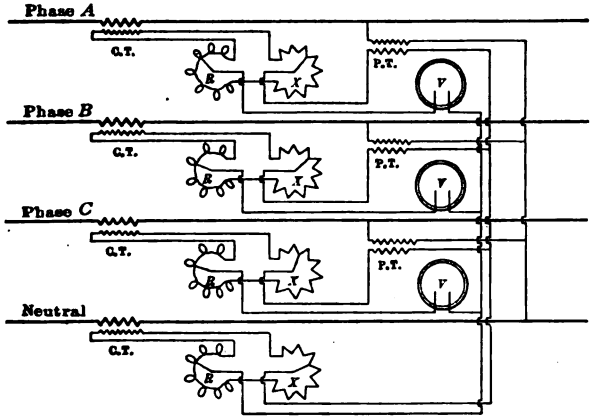


FIG. 25.—Compensator connections for three-phase four-wire system.

should be set at 2.5 per cent. on each dial; that on the neutral should be set at 2 per cent. on each dial, to take care of unbalanced load. If, however, the *A*-phase branches off with a neutral to a single-phase centre of a distribution 2,500 ft. beyond, there must be added to the *A*-phase setting, $2 \times 100 \times 2.5 \times 0.098 = 49$ volts $= 2.2$ per cent., making the new setting $2.5 + 2.2 = 4.7$ per cent. If the other phases branch to similar centres of distribution, at different distances, the drops must be computed similarly, and added to the three-phase drop. The connections of the compensators for a three-phase, four-wire feeder are shown in Fig. 25.

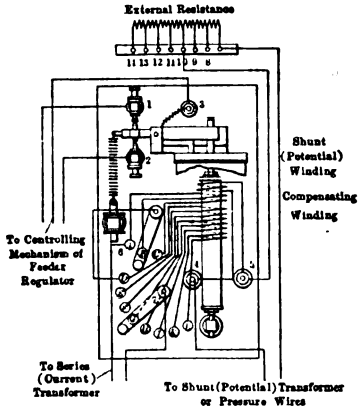


FIG. 26.—Automatic regulators for controlling feeder voltage.

93. Automatic regulation of feeder voltage. In connection with automatic regulation the General Electric Co. has developed a device which serves as a line-drop compensator combined with a relay. This device, known as a "**contact-making voltmeter**," is shown in Fig. 26. It consists of a solenoid having windings which are tapped at various points and brought out to adjustable switches, as in the line-drop compensator. One winding produces a magnetic flux proportional to the pressure; another carries current in proportion to the load and opposes the flux due to the feeder pressure. This counter-

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magnetomotive force may be adjusted roughly by setting the proper switch on the points *A*, *B*, or *C*, and the finer adjustments are made by the points *D* to *L*. The pivoted bar carries the contacts which control the supply of energy to the feeder regulator.

As the load increases, the plunger falls until the contact is made which raises the pressure on the feeder. This increases the flux due to the pressure and the plunger rises sufficiently to stop the movement of the regulator until a further change in load or bus pressure occurs. This device gives very satisfactory results at all power-factors from 75 per cent. to 100 per cent.

94. Bus-bar voltage regulation. Where there is a variable motor load supplied by motor-generator converting equipment, it is desirable to maintain a constant bus pressure, in order to prevent the load variations from affecting the bus pressure and thus impairing the steadiness of voltage on the feeders supplying the lighting service. The automatic regulator devised by Tirrill has been successful in accomplishing this purpose.

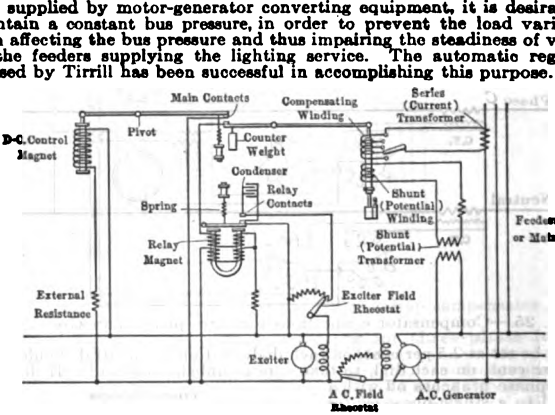


FIG. 27.—Connections of Tirrill regulator.

95. Tirrill regulator. The general scheme of connections is shown in Fig. 27. The secondary circuits of the shunt (potential) and series (current) transformers in the generator leads are connected through a solenoid in a compounding relation. The series section is subdivided so that different rates of compounding may be secured. A movable plunger is actuated by this solenoid, which in turn actuates a counterweighted lever, the opposite end of which is equipped to make electrical contact in a relay circuit. The other contact terminal of this relay circuit is carried on a similar lever which is actuated by the plunger of a direct-current solenoid. This solenoid receives current in proportion to the pressure at the exciter terminals. The relation of these contact-making levers is such that increased pressure at the exciter brushes tends to open the relay circuit, while increased pressure at the main generator terminals tends to close it.

This closing of the circuit demagnetizes the relay, which is differentially wound, and its armature is withdrawn by a spring. This shunts the field rheostat of the exciter, increases its terminal pressure, and opens the relay circuit, thus weakening its pull.

Where there are several units in parallel in a station, the regulator may be applied to the exciter for a portion of them and the bus regulated for constant pressure with the series coil of the alternating solenoid cut out. With this arrangement, the bus pressure may be maintained constant at any desired value by the insertion of an adjustable resistance in the pressure circuit of the alternating solenoid.

SECONDARY DISTRIBUTION

96. The secondary mains of an alternating-current system serve users in a local area, while the primary mains supply larger areas. The standard system of secondary distribution in America is the **single-phase,**

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three-wire Edison system at approximately 110–220 volts for lighting and small motor service, and 220-volt two-phase or three-phase for general motor service; 440 volts and 550 volts are also used to some extent for power systems in industrial plants. For the supply of mixed service of lighting and motors from a secondary network, the **four-wire, three-phase system** at 115–200 volts or 120–208 volts, approximately, is sometimes used.

97. The voltage of general distribution systems must be low enough to be adapted to incandescent lamps, fans, heating devices and other small accessories, which are preferably made for the voltages around 110. Motor voltages are higher in order to secure economy of conductor investment; this is especially true with large installations.

98. Transformers are usually wound for a ratio of 2,200 to 110–220 volts, though some of the systems where 115–230 volts are standard are using a ratio of 2,080 to 115–230 volts. This secondary voltage permits a spacing between transformers of 600 ft. to 800 ft.

99. In laying out secondary systems for lighting service, it is usual to limit the drop from transformer to consumer to about 2 per cent. where first-class service is required. In scattered districts where secondaries are too small and remote to warrant interconnection, the problem of design consists in striking a balance between the cost of conductors, and the cost of transformers and their losses.

By reaching out farther from the transformer with the secondary mains, the number of transformers is reduced, and, their average size being larger, their total cost is smaller. This is true because the cost per kilowatt is less for the larger sizes, and because the kilowatt capacity required per kilowatt connected is less for a large number of users than for a few.

100. Minimum annual cost. As the radius of distribution from the transformer becomes more than 500 to 600 ft., the cost of conductors increases very rapidly, and it becomes more economical to provide additional transformers. On the other hand, if too many transformers are used, the iron loss which goes on 24 hr. a day becomes excessive, and the investment per kilowatt in transformers is high. The minimum annual cost of a secondary system is that at which the fixed charges on conductors and transformers, plus the value of the iron loss, is a minimum. The iron and copper losses of standard American transformers appear in the table in Par. **101** (also see Sec. 6).

101. Losses and Efficiencies of Standard Transformers for Alternating-current Distribution

2,200 to 110–220 volts, 60 cycles

Rating kv-a.	Watts loss		Per cent. efficiency, full load	Per cent. regulation		Per cent. charging current.
	Core	Copper at 125 deg. fahr.		100 per cent. p-f.	80 per cent. p-f.	
1	20	26	95.8	2.61	3.18	5.5
1 1/2	25	37	96.2	2.47	3.10	4.0
2	30	46	96.5	2.33	3.00	3.6
3	34	70	96.8	2.36	3.01	3.0
5	40	82	97.2	2.08	3.12	2.5
5	45	102	97.3	2.08	3.10	2.3
7 1/2	62	137	97.6	1.84	2.93	2.2
10	80	163	97.8	1.66	2.85	1.9
15	105	233	97.9	1.58	2.80	1.6
20	131	295	98.0	1.52	2.96	1.5
25	147	351	98.2	1.47	2.90	1.3
30	163	411	98.2	1.46	2.90	1.2
40	205	476	98.3	1.30	2.80	1.2
50	240	605	98.4	1.20	2.70	1.0

Also see Sec. 6.

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102. All-day efficiency of transformers. In a distribution transformer, the iron loss may reach a considerable percentage of the daily consumption of energy. A 5-kw. transformer which carries full-load 4 hr. a day delivers 20 kw-hr. per day, and has a copper loss of about 102 watts at full-load, while the iron loss would be about 45 watts. The copper loss per day would be about 410 watt-hr., while the iron loss would be $24 \times 45 = 1{,}080$ watt-hr. The total loss being 1.5 kw-hr., the all-day efficiency is $20/21.5 = 93.0$ per cent., and the full-load efficiency is $5{,}000/5{,}150 = 97.1$ per cent. It is apparent that the all-day efficiency varies with the **load factor** or hours' use of the maximum load.

103. Calculation of secondary mains. The most economical size of conductor and spacing between transformers for secondary mains may be determined approximately as follows:* assuming a load density per 1,000 ft. and an allowable pressure drop, determine the distance between transformers which will result in that drop with several sizes of conductor.

The investment in wire and transformers may then be found. The fixed charges on the investment plus the annual value of the iron losses in the transformer constitute the annual cost of this secondary main (exclusive of pole line or conduit). The minimum annual cost will be found to work out approximately as in the curves shown in Fig. 28.

104. Curves of cost variation, overhead distribution. The variation of the elements of cost as the spacings between transformers and the size of wire are changed, is illustrated by the curves in Fig. 28, which are based upon a load density of 50 kw. per 1,000 ft., with overhead lines. It is apparent from this curve that the minimum cost is found with No. 2 wire at a spacing of 600 ft. between transformers. The curves of total cost at other load densities are shown in Fig. 29. These figures are based on 10,000 ft. of secondary main.

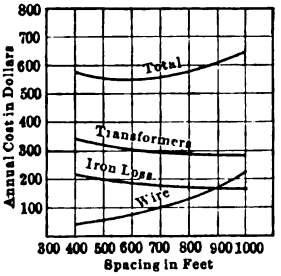


FIG. 28.—Elements of cost of secondary main.

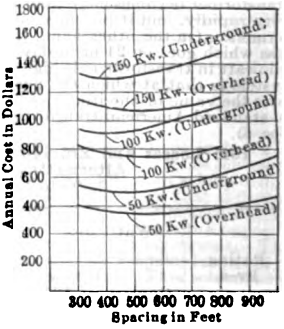


FIG. 29.—Economical spacing of transformers.

Where energy may be charged at less than 1 cent per kw-hr., or with water power, the decreased value of core loss tends to permit the use of smaller transformers, shorter spacings and a smaller size of wire.

105. Curves of cost variation, underground distribution. The curves for underground lines also appear in Fig. 29. The spacing for minimum cost is not materially changed, being about 500 ft. for each load density.

The flatness of the curve of total cost allows considerable flexibility in spacing, and it is generally preferable to use as few transformers as possi-

*Gear and Williams. "Electric Central Station Distributing System," p. 108.

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ble with the larger sizes of conductor, so as to reduce the number of units to a minimum. Furthermore, it is usually desirable to **anticipate an increase in load** by installing a larger conductor than is required for immediate needs. The size of transformers is then gradually increased, from time to time, as the load increases.

106. Uneven load density. The curves (Figs. 28 and 29) are based on an assumption that the load is uniformly evenly distributed along the line throughout its length, but such is rarely the case in practice. At occasional intervals, department stores, churches or other large customers of energy throw heavy loads upon the line. It is necessary, therefore, to locate transformers near such large consumers' premises and design the mains between them to carry the scattered load.

107. Secondary networks. The gradual extension of mains on all streets results in a system of lines which is interconnected and becomes a network. **Transformers are preferably located** at intersections where they feed in all directions with the best economy of copper. In the design of such networks the sizes of secondary cable are fixed by the local conditions. The smaller consumers distributed along the routes are carried from mains of proper size, and the larger consumers such as theatres and department stores are cared for by a separate installation of transformers in the immediate vicinity of the consumers' premises.

108. Underground construction is often required in networks and this necessitates **manholes** of ample size for large transformers and such junction boxes as are necessary for operation. The space required is somewhat difficult to secure on account of pipes and other underground systems which limit the available space. In some cases it has been found desirable to install the transformers in a substation, supplying the network through low-tension feeders; this arrangement permits a saving in transformer investment and iron losses, as the diversity factor is better and the units are larger, but the cable investment is considerably greater.

109. Separate transformers for large motor loads. The design of secondary systems is subject to restrictions when **inductive loads,** such as arc lamps and motors, must be served along with incandescent lighting. The heavy starting-current required by induction motors may momentarily overload the transformer and the secondary main. This causes a flickering of incandescent lamps served in the vicinity. It is necessary, therefore, to install separate transformers for installations of motors if the best regulation is required for incandescent lighting. Motors larger than 10 h.p. can not usually be supplied from a lighting network without interfering with the service.

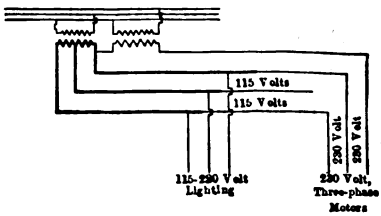


FIG. 30.—Three-phase secondary system, with single-phase lighting service.

110. Three-phase supply for mixed loads. In three-phase systems several methods of carrying mixed lighting and motor loads are in use. The most common method consists of **star-connected transformers supplying a four-wire main** operated at about 115 volts from phase to neutral and 200 volts across phase wires. The smaller lighting services are made three-wire and connected to two phases and neutral, and large services are balanced on three phases. Four-wire service is required wherever both lighting and motor service are supplied.

In another method, illustrated in Fig. 30, all the lighting is carried single-phase from a three-wire Edison main. Motors are served by the installation of additional smaller transformers and a fourth secondary (phase) wire. The lighting load is easier to keep balanced, and the higher diversity factor requires somewhat less transformer capacity for lighting.

111. Determination of transformer capacity. The selection of the size of transformers for various classes of consumers is important, since

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excess capacity involves idle investment and unnecessary core losses. Very few consumers use their entire connected loads at any one time. Where a number of consumers are served by one transformer, the various *maximum demands do not occur simultaneously* and therefore the resultant maximum demand is less than the sum of the individual demands. The demand must be ascertained by measurements which may be made by means of an ammeter or by a **Wright demand** indicator (Sec. 3).

Certain **ratios of maximum demand to connected load** may be established by a series of such measurements for the various classes of consumers for which it is necessary to select transformers. These ratios or **demand factors** (Par. **112** to **118**) may then be applied with reasonable accuracy to the transformers for new consumers. The results of tests made on various groups of consumers in Chicago appear in Par. **112**.

112. Table of Demand Factors in Lighting Service
(Based on Chicago Experience)

Description of load	Number of customers	Kilowatts connected	Kilowatts demand	Demand factor (%)
Residence	137	84.7	18.9	22.3
Residence	68	126.6	15.75	12.4
Residence (119 kw.; stores 11 kw.)	196	129.5	28.85	22.3
Residence (1 customer, 7.5 kw.)	5	10.3	9.45	92.0
Residence 70 kw.; stores 7 kw.	77	77.0	21.0	27.3
Residence (59.7 kw.; hotel 48 kw.)	66	107.7	26.25	24.3
Residence (1 30-amp. rectifier)	121	183.5	30.5	16.6
Residence	34	47.5	10.5	22.2
Residence (2 30-amp. rectifiers)	19	79.2	15.7	19.8
Residence (1 30-amp. rectifier)	21	67.7	13.6	20.2
Residence (1 30-amp. rectifier)	21	54.1	13.1	24.3
Residence	47	68.7	8.4	12.2
Residence	144	129.95	22.6	17.4
Residence (4 30-amp. rectifiers)	43	59.0	26.6	42.0
Residence	85	99.65	16.1	16.1
Residence	84	112.5	14.7	13.2
Residence, 20 kw.; Stores 15.7 (hotel 25 kw.)	38	60.7	27.3	45.0
Residence	99	59.0	8.4	14.2
Residence	89	100.45	13.7	13.6

113. In store lighting the maximum demand for window lighting, signs and other display lighting is from 90 per cent. to 100 per cent. of the connected load. The demand on interior store lighting is from 50 per cent. to 70 per cent.

114. In residence lighting where the connected load is fifty lamps or less, the average demand factor of a group of residences is from 15 per cent. to 20 per cent. of the connected load; small residences and apartments having connected loads of forty lamps or less, average about 20 per cent. of the connected load.

115. In theatre lighting the border lamps and foot lamps, of several colors, are not used simultaneously; and the stage and the auditorium are not lighted simultaneously except for a very few minutes at a time. In a small theatre the demand factor may be from 70 per cent. to 85 per cent., while in a large theatre it frequently runs as low as 50 per cent.

116. Influence of number of consumers on demand factor. In general, a higher ratio must be used where but few consumers are served from one transformer, than where there are more, as the occasional maximum demands of individual consumers are proportionately much larger.

117. The selection of transformers for motor loads is more difficult, as the maximum load may vary greatly from day to day or from month to month. Elevator and crane motors require transformers having 100 per cent. to 125 per cent. of the rated motor capacity, unless there are several motors

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supplied by one unit. This is necessary in order to hold up the pressure in starting. The average demand factors in motor service in Chicago are given in Par. **118.** These figures were made up from several thousand installations of continuous-current motors in Chicago, which were equipped with maximum-demand meters.

118. Table of Demand Factors in Motor Service
(Based on Chicago Experience)

Total installation in h.p.	Number of customers	Total h.p. connected	Average maximum h.p.	Ratio of max. to conn. h.p.
1 motor,				
1 to 5.....	1177	2165	1862	86.1
6 to 10.....	124	1036	676	65.3
11 to 20.....	32	492	303	61.6
above 20.....	17	686	366	53.2
Total.....	1350	4379	3207	73.3
2 motors,				
1 to 5.....	177	412	285	69.1
6 to 10.....	51	387	261	67.4
11 to 20.....	30	438	288	65.9
above 20.....	6	203	74	36.5
Total.....	264	1440	908	63.0
3 to 5 motors,				
1 to 5.....	150	381	314	82.5
6 to 10.....	42	290	238	82.1
11 to 20.....	33	475	329	69.3
above 20.....	14	1245	657	52.7
Total.....	239	2391	1538	64.3
6 to 10 motors,				
1 to 5.....	42	121	80	66.0
6 to 10.....	21	157	98	62.4
11 to 20.....	10	155	98	63.1
above 20.....	19	931	417	44.7
Total.....	92	1364	693	50.8

SPECIAL METHODS OF TRANSFORMATION

119. General. The use of various primary and secondary voltages and systems gives rise to situations, at times, which require the distribution engineer to make use of special methods of transformation. Some of the combinations of apparatus and connections which are most likely to be used are presented herewith.

120. The connections of standard transformers are made with two primary and two secondary coils, which permits their use on 2,200-volt or 1,100-volt circuits. The secondary may be connected for 110 volts or 220 volts, or on the three-wire Edison system at 110–220 volts. Some systems use a transformer having windings for 1,040–2,080 to 115–230 volts.

121. Booster transformers. Where it is desired to raise or lower the pressure by a fixed percentage, as when line drop is excessive, this may be accomplished by a transformer used as a booster. This is a transformer so connected that the secondary is in series and in phase with the main line and thus the primary pressure is raised by the amount of the secondary voltage, as shown in Fig. 31.

When the secondary is reversed, the transformer becomes a "choke," or **negative booster** depressing the line pressure instead of raising it. The connections for 5 per cent. and 10 per cent. "boost" are shown in Fig.

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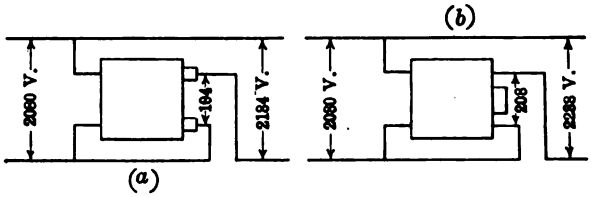


FIG. 31 —Booster transformer connection for positive boost.

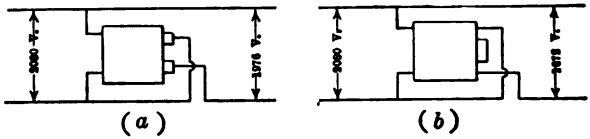


FIG. 32.—Booster transformer connections for negative boost or choking.

31, at *a* and *b* respectively. The corresponding connections for 5 per cent. and 10 per cent. choke (negative boost) are shown in Fig. 32.

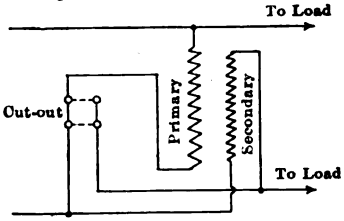


FIG. 33.—Connections of booster cut-out.

It is to be noted that the transformers used in these illustrations have a ratio of 10 to 1 or 20 to 1, and these percentages apply only to boosters having this ratio of transformation. If boosters having a ratio of 2,080 to 115–230 are used, the percentages are increased to about 5.5 per cent. and 11 per cent., respectively.

122. Precautions when installing boosters. If the primary of the booster is opened while the secondary is carrying the line current, the booster acts as a series transformer. The primary coils then generate a potential of 10,000 volts to 20,000 volts, or more, depending upon the load carried by the main circuit at the time. If a fuse is used in the primary, the blowing of the fuse will create this condition and the arc will hold across the terminals of the block, and is quite sure to break down the insulation of the primary coil.

The safest method of connecting or disconnecting a booster is to have the main line open while connecting it in or out of circuit. If the service cannot be interrupted, or if it is desired to switch the booster in or out at certain times, this may be accomplished by the use of a **series cut-out**, connected as shown in Fig. 33. The cut-out simultaneously opens the primary and short-circuits the secondary of the booster. Standard series-arc cut-outs should not be used where the line current is likely to be over 25 amp.

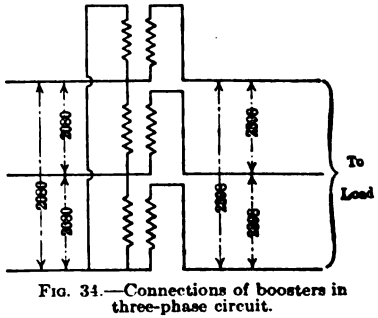


FIG. 34.—Connections of boosters in three-phase circuit.

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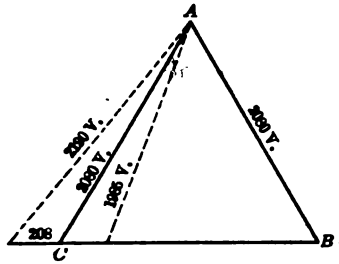


FIG. 35.—Effect of booster in one phase of three-phase circuit.

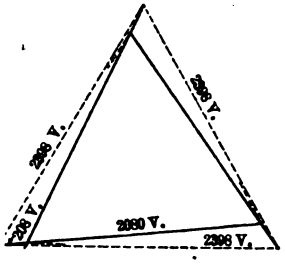


FIG. 36.—Effect of boosters in each phase of a three-phase circuit.

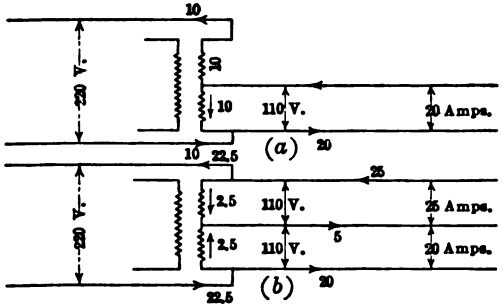


FIG. 37.—Connections of auto-transformers for 110-volt lighting.

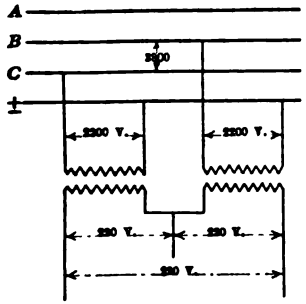


FIG. 38.—Open-delta connection of two transformers supplied from a three-phase four-wire system.

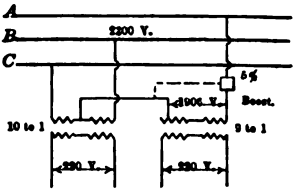


FIG. 39.—Transformation from three-phase to two-phase, or *vice versa*, with tee-connection.

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123. The use of boosters in a delta-connected three-phase system is not so simple as in single-phase circuits. The booster secondary is looped into the line and pressure is taken for the primary from an adjoining phase, as in Fig. 34. The insertion of a booster on one phase affects the pressure on two phases, as shown diagrammatically in Fig. 35. The effect of a booster in each phase is shown in Fig. 36. Three boosters are required, therefore, to keep conditions in balance, in a three-phase three-wire circuit.

124. Auto-transformers. The use of 110-volt incandescent lamps in a 220-volt or 440-volt alternating-current system may be accomplished quite readily by the use of standard transformers used as auto-transformers. The connections in Fig. 37 show the methods of deriving two-wire and three-wire 110-volt distribution from a 220-volt system. When the lighting service is handled on a three-wire basis at 110–220 volts, the transformer carries only the unbalance of current; the primary winding is not used. Where 110-volt service is desired from a 440-volt plant, it may be secured from two transformers connected in series on the 220-volt side and in parallel on the primary side.

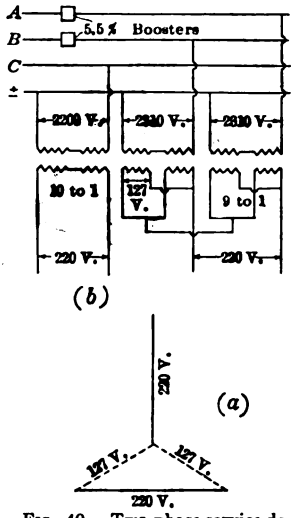


FIG. 40.—Two-phase service derived from a three-phase four-wire system with three transformers.

125. Three phase conversion with two transformers. Service may be given from two transformers to three-phase power users by the open delta or by the tee (T) connection, thus reducing the investment in transformers for the smaller users.

The open delta connection from a three-wire system is the usual delta connection (Sec. 6) with one transformer omitted. The connection from a four-wire system is shown in Fig. 38, two of the phase wires and the neutral being used on the primary side of the transformers. With the open delta connection the current in the transformer coils is 15.4 per cent. greater than with three transformers for the same load and the capacity of the transformers must be sufficient to carry the extra current. For instance, if three 10-kw. transformers are fully loaded, the line current is 1.73 times the current in the transformer coils. If two 15-kw. transformers are substituted for the three 10-kw. units, the capacity of the coils is 1.5 times greater than in the 10-kw. unit but the line current is 1.73 times greater, and the coils of the 15-kw. unit are therefore overloaded in the ratio $\frac{1.73}{1.5}$ = 1.154 or 15.4 per cent.; or the two 15-kw. units have but 86.7 per cent. of their normal capacity.

In the **three-phase three-wire** system, service may be given from two transformers with the **tee (T) connection** (Sec. 6). The current overload is 15.4 per cent.; as with the open-delta connection. This scheme cannot be used with standard 2,200-volt transformers on a four-wire system, as the principle of operation requires that the current divide and pass each way from the midpoint of the winding of one of the transformers, so that the magnetic field of one part balances the other.

126. Conversion from three-phase to two-phase, or vice versa. The **tee-connection** may be used in transforming from three-phase to two-phase, or *vice versa*, as shown in Fig. 39. with standard transformers having ratios of 9 to 1 and 10 to 1 respectively. If transformers having a ratio of 10 to 1 are available only, the right-hand transformer (Fig. 39) should be given a positive boost of 15 per cent. instead of 5 per cent. When using transformers having ratios of 9 to 1, the left-hand unit should be given a 10 per cent. negative boost, and the right-hand unit a 5 per cent. positive

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boost, in order to give 220-volt two-phase service from 2,200-volt primary mains.

127. Two-phase 220-volt service from a three-phase four-wire system may be secured with three standard transformers, connected as shown in Fig. 40. The unit at the left has a ratio of 10 to 1, and is connected from phase to neutral. The other two have ratios of 9 to 1, with their secondary coils in multiple, and are arranged as two limbs of a star-connection (Y), to give 220 volts across the outer wires. The three-phase system is therefore unbalanced by this arrangement, since half the energy is taken from one phase. The capacities of the transformers should be selected accordingly.

It is possible to use transformers with ratios of 10 to 1, but if this is done each of the phases supplying the right-hand transformer must be provided with a boost of 15 per cent.

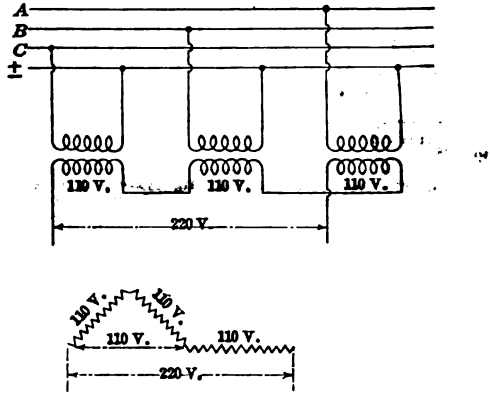


Fig. 41.—Conversion from three-phase to single-phase, with balanced load.

128. Conversion from three-phase to single-phase. When single-phase energy is required for a relatively large unit of load such as a welder or brass furnace, it is undesirable to supply it from one phase of a three-phase supply, as the unbalanced load interferes with pressure regulation and may overload one phase before the line, as a whole, is fully loaded.

The load can be distributed between the phases in the ratio of 50, 33 and 33 approximately, by connecting the single phase load to one phase of a delta-connected three-phase transformer installation. This is applicable in a 3-wire or in a 4-wire primary system. With a 4-wire system the method of connection in Fig. 41 is sometimes used. This requires capacities in the ratio 50, 50 and 50 and gives poor regulation of pressure. The current drawn from the three phases is equal but the power factor on two of the phases is low and the energy is not balanced equally on the phases.

PROTECTIVE APPARATUS

129. The insertion of fuses for protection in low-tension lighting systems has become universal, because of the low cost of fuses as compared with circuit breakers. In power systems where the circuits are opened frequently, the circuit-breaker is found preferable.

130. Plug-fuses. The fire hazard from the flash which occurs at the melting of a fuse led to the development of **enclosed fuses**, the earliest of which was the Edison plug-fuse, which is used very generally on circuits up to 20 amp.

131. Cartridge fuses. Cartridge fuses, consisting of a tube of fibrous material in which the fuse is mounted, with a filler of fire-resisting powders are used largely on circuit operating at 250 to 600 volts. Cartridge fuses

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have been fully standardised by the National Electrical Code as to voltage and current as follows: 250-volt: 0–30 amp., 31–60 amp., 61–100 amp., 101–200 amp., and 201–500 amp.; 600-volt: 0–30 amp., 31–60 amp., 61–100 amp., and 101–200 amp.

132. The law of the operation of fuses was discovered by Preece in 1888. It may be stated in the form,

$$\text{Current} = a\sqrt{d^3} \qquad (6)$$

d being the diameter of the wire expressed in inches. The value of the constant "a" varies with the kind of metal used. For copper it is 10,244; for aluminum 7,585, for lead 1,379, for tin 1,642 and for iron 3,148.

133. Fusing Currents of Copper and Aluminum Wires

	Size of wire, A.W.G.						
	8	10	12	14	16	18	20
$\sqrt{(d)^3} =$	0.046	0.0325	0.0229	0.0162	0.0114	0.0081	0.0057
Fusing current of copper (amp.)	472	334	235	166	117	83	58
Fusing current of aluminum (amp.)	349	246	174	123	86	61	43

134. The protection of a distributing system is necessarily a compromise among conflicting conditions. Location of fuses should be such that the area affected by the operation of a fuse is as small as possible. On the other hand a fuse is prone to operate when it should not; therefore fuses should not be multiplied unnecessarily.

135. Fuses in overhead alternating-current lines. Where the mains are not interconnected, experience has demonstrated that very few fuses should be used. The principal branches should be provided with **disconnect-switches** which can be readily used in locating trouble, and the use of fuses should be limited to branches where there is a continuous hazard such as trees, or a very long run which is otherwise exposed. When a branch or feeder is in trouble, it is isolated by the use of disconnect-switches and all dependent branches affected are transferred to adjoining circuits through emergency disconnect-switches provided for the purpose.

136. In underground low-tension networks, the sectionalizing (with fuses) must be done with great thoroughness owing to the density of the load, the length of time required to make repairs and the importance of the service. Trouble on a distributing main should be limited to the block in which it occurs, and if lines are carried on both sides of the street, to one side of the street. It is practice to place fuses at all junction points in networks. **Sheet-copper fuses** are generally used for this purpose. The section of the copper where fusion takes place is designed to fuse at about twice its normal load.

137. The feeders are fused at the point where they connect into the network, to protect the network against trouble on the feeder. It is not usual to provide fuses on low-tension feeders at the station, as the operator on duty can open the switch in case it is necessary.

138. Fuses at subway transformers. When the network is fed by subway transformers, an additional link is introduced in the system. Both sides of the transformer should be connected to the system through **junction boxes** so that the unit can be easily cut off from the system if it burns out.

139. Line transformers should be provided with primary fuses of such size that they will not blow unnecessarily. The **porcelain type** of fuse furnished with the transformer has proven very satisfactory for transformers up to 20 kw. **Aluminum is used as the fuse metal** up to 15 amp. or 20 amp. at 2,200 volts. Above 25 amp. various types of fuse have been tried, but the amount of energy concentrated at the arc makes the problem difficult. Some of these give promise of success, but practice is not at all standardised. The cartridge fuse is effective to 50 amp., but it is difficult to keep it dry enough to prevent the filler from absorbing moisture when used out of doors.

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140. Circuit-breakers are the preferable means of protection where automatic cut-outs operate at frequent intervals, and also for circuits operating at high voltages, controlling loads of 100 kw. and upward. In general, the circuit-breaker is expensive in first cost but inexpensive in operation, while the use of fuses involves a considerable maintenance charge, but small first cost.

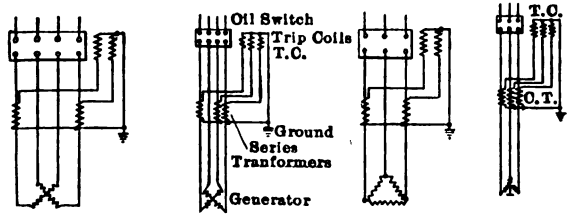
On low-potential circuits the circuit-breaker consists of a switch of suitable design, with which is combined a series coil so arranged that it lifts a movable core and releases a spring-actuated mechanism which opens the switch. Circuit-breakers are designed so that they may be adjusted to operate at any point between 80 per cent. and 150 per cent. of their rated capacity.

In **high-potential systems** a series transformer may be installed at a convenient point to operate the tripping-coil of the circuit-breaker. On circuits operating at pressures above 600 volts the switch is designed to break in oil.

141. The operating mechanism of the circuit-breaker may be controlled by hand, or electrically by means of solenoids. In **hand-operated breakers** the energy required to open the circuit is stored in springs compressed during the act of closing. In **electrically operated breakers** the power for both closing and opening the circuit is supplied through solenoids or motors.

The larger sizes of circuit-breakers and those operating at the higher voltages are usually controlled electrically, on account of the power required, and because of the greater facility of operation. Continuous current is usually available in generating stations and substations, from the exciter system, and is therefore used for the operation of solenoid-controlled breakers where possible. Motor-operated breakers are often equipped with alternating-current motors.

142. Relays. It is usual to design relays for operation with an **inverse time element**; that is, with a relay set to operate at 100 amp. after 10 sec., it will operate at about 300 amp. in 5 sec. and almost instantaneously at 1,000 amp. This characteristic gives prompt action in opening the line under short-circuit, while reducing the likelihood of unnecessary interruption under brief overloads.



Two-phase. Two-phase; Phases Interconnected. Three-phase. Three-phase; Grounded Neutral.

FIG. 42.—Relay arrangements for two-phase and three-phase circuits.

143. The arrangement of relays must be such that a short-circuit between any two wires will operate the breaker. On single-phase circuits one relay is sufficient to accomplish this. On two-phase systems supplying lighting and motor service it is desirable to provide separate relays and circuit-breakers for each phase. In the three-phase, three-wire system without grounded neutral, relays are required in two of the three wires; the three-pole type of circuit-breaker is used. In the three-phase, four-wire system having the neutral point grounded, it is essential that relays be installed in each phase wire, with single-pole breakers; in case of a ground on one phase the corresponding circuit-breaker opens without interrupting the lighting service on the other phases (Fig. 42).

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144. Relays on three-phase transmission lines. It is customary to provide relays at the point of supply, commonly called **overload relays**. Where several lines are operated in parallel, further protection is necessary. When the lines are connected to the same bus at each end, a short-circuit will draw energy from both ends and circuit-breakers must be provided at both busses. The relays at the receiving end must, however, be of a type which will operate only on reversal of the flow of energy. The converting equipment is provided with reverse-power relays on the secondary side.

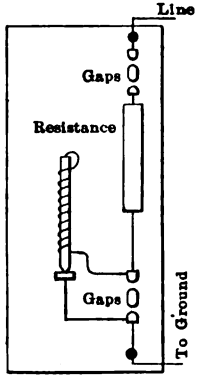


FIG. 43.—Solenoid type of lightning-arrester.

145. Speed-limiting devices. It is important that synchronous converters be protected by speed-limiting devices designed to operate the direct-current circuit-breaker when the speed exceeds a safe value.

146. Lightning Protection. Overhead distributing lines are susceptible to the effects of lightning. A discharge among the clouds causes an abrupt discharge of potential on the wires, which must be given an opportunity to escape to earth without injuring the insulation of the apparatus.

147. The function of lightning-arresters is to protect apparatus by passing the discharge of lightning to ground, without permitting the arc thus established to be maintained. This may be accomplished on potentials up to 600 volts by a short gap of non-arcing metal. At 2,200 volts or higher, several gaps in series are necessary, with a resistance to limit the current. Since each wire of the circuit is affected, discharge gaps must be provided between each wire and ground.

In systems having one side grounded, every discharge is likely to be followed by the generator current, as there is a fixed difference of potential between the circuit and earth. Arresters on grounded systems must, therefore, meet more severe requirements than those on ungrounded systems.

The problem of protection of transmission lines becomes more complex as the voltage is increased, and the study of protective methods for lines operating at 20,000 volts and upward is leading to new developments every year. The discussion in this Section will be restricted to alternating-current distributing systems operating at less than 5,000 volts.

148. Types of Arresters. The wide range in severity of lightning flashes makes it well-nigh impossible to design an arrester which will protect apparatus and yet withstand the effects of a direct stroke at any point nearby. The arresters described in the succeeding paragraphs (Par. **149** to **152**) include the leading commercial types which have been used in distribution work.

149. The Garton-Daniels arrester, Fig. 43, consists of air gaps and resistances, with a solenoid so arranged that the plunger is raised by the passage of the generator current, thus placing additional gaps in series and rapidly diminishing or stopping the flow of energy. The lightning discharge passes across the shunted gaps to ground owing to the inductance of the solenoid.

150. Multi-gap arrester. A modification of the spark-gap and resistance type of arrester has been employed quite extensively. This is illustrated in Fig. 44, as made for 2,300 volts, and consists of three paths of discharge, one of which has a high

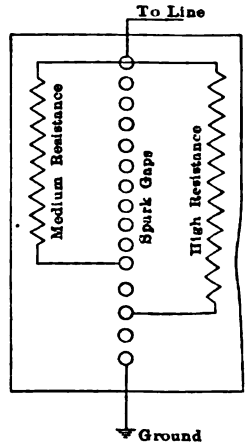


FIG. 44.—Multi-gap lightning-arrester.

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resistance (100,000 ohms), another a resistance of about 300 ohms, and a third which consists of 13 or 14 gaps without resistance. The impedance of the unit is such that discharges of very high frequency pass over the 13 gaps, while those of lower frequency pass over the smaller number of gaps through one of the resistances. A slightly modified form is shown in Fig. 45.

151. The aluminum-cell arrester has given good results because of its ability to stop the flow of current promptly and safely. It has been found especially valuable at transmission voltages where its expense is justified by the importance of the service. It is not suited for outdoor distribution work, since it requires daily charging and supervision and cannot be left continuously in circuit.

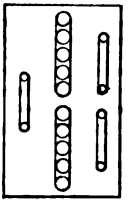


FIG. 45.—Westinghouse low equivalent arrester.

152. The compression type of arrester, Fig. 46, consists of a series resistance with air-gaps, assembled inside of a porcelain tube, the top of which is capped and sealed. The air-gaps are surrounded by a grounded strip of iron outside of the tube, which acts as a means of equalising the potential gradient. The discharge of the arrester expands the air and compresses it, since the tube is sealed; hence the name compression type. This arrester, having but one path to ground, is of limited capacity.

153. Location of arresters. All of the above-described types of arresters are in general use on distributing systems in America, and each gives reasonably good protection to apparatus when placed in its immediate vicinity. Experience has fully demonstrated that lightning discharges do not travel any great distance along a line, owing to the very high frequencies of this form of energy. The arrester must, then, be located as near the apparatus as practicable, and preferably on the same pole. Complete protection of distributing transformers would require that an arrester be placed on every transformer pole.

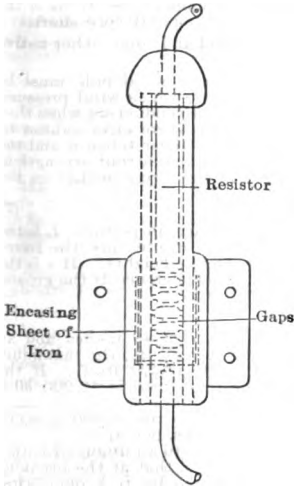


FIG. 46.—Compression lightning-arrester.

The experience of large companies, however, has been that the cost of the damage to apparatus from lightning is not as large as the fixed charges on the arrester equipment, when complete protection is provided. The exact point at which these two elements of cost become a minimum varies with the value and the size of the transformers, since it costs as much to protect a 1-kw. unit as a 50-kw. unit. The tendency is toward the use of arresters on all transformers since the interruption of service in time of storm is greatly reduced by the presence of arresters

154. The use of lightning-arresters on transformer poles has been found to materially diminish the number of interruptions of service due to blowing of transformer fuses, and this tends to make the more liberal use of arresters desirable.

OVERHEAD CONSTRUCTION

155. General. Overhead construction is an economic necessity in a large part of every city. The **investment** for overhead lines in outlying districts usually is from 15 per cent. to 30 per cent. of that required for underground construction, and it is obvious that overhead construction must be used wherever feasible, to keep the investment within profitable limits.

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In many cases the objection to overhead lines is minimised by locating them in alleys.

156. Poles. Distribution lines are necessarily carried on wooden poles. Iron poles are objectionable on account of the risk to linemen in handling "live" primary circuits. Iron poles are used in some cases for street-lighting circuits which are so operated that it is not necessary to do any work on them while they are "alive." The cost of iron poles is about twice that of wooden poles.

157. Concrete poles are being used increasingly in sections where the ravages of insects and the nature of the soil make the life of wooden poles very short. They are also being introduced for transmission work in places where iron poles would otherwise be required.

158. The woods which are best suited for pole work are Michigan cedar, Western cedar, chestnut, pine, and cypress.

159. The Michigan cedar grows with a natural taper of about 1 in. in diameter to every 5 ft. or 6 ft. of length, making a very substantial and rigid pole.

160. The Western cedar, which grows in Idaho and Oregon, has a natural taper of about 1 in. in 8 ft. to 10 ft. of length. For the same size of top the diameter of the butt is, therefore, smaller than that of the Michigan cedar. The surface of Western cedar is smoother than that of the Michigan cedar and the poles are very straight and neat in appearance. It is necessary on important lines to use nothing smaller than 8-in. tops with these poles, in order to secure adequate diameter at the ground line.

161. The chestnut pole is quite different from the cedar poles. The specific gravity of the wood is high and the surface is irregular and knotted, making the appearance of the chestnut pole not as good as that of cedar.

162. Pine and cypress poles are more like cedar in their general characteristics of weight and strength. Their use is limited to sections of the country where the timber is native, as their life is comparatively short.

163. On the Pacific coast, California redwood and some other native woods are used very generally.

164. Strength of wood poles. The strength of a wood pole must be sufficient to withstand the transversely acting forces, such as wind pressure, on the pole and conductors, the unbalanced pull on the conductors when they are broken and the side pull on curves and corners where guys cannot be provided. These forces place the fibre of the wood under tension and the load which a given pole will carry is determined by the inherent strength of the wood fibre under tension and the moment of the forces acting on the pole. The moment is

$$M = PL + P_1L_1 + P_2L_2 \text{ etc.}, \tag{7}$$

in which P represents the force acting at one cross arm in pounds, L is the height at which the arm is attached in feet, P_1 and P_2 etc., are the forces acting on other arms and L_1, L_2 etc., are the respective heights. If s is the fibre stress in pounds per square inch, and c is the circumference at the ground in inches, the allowable moment of a pole of given size is

$$M = 0.0002638sc^3 \tag{8}$$

Thus for a pole having a ground-line circumference of 40 inches and an allowable fibre stress in an emergency of 2500 lbs. per sq. in., the maximum allowable moment is $M = 0.0002638 \times 2{,}500 \times (40)^3 = 42{,}200$ lb.-ft. If the average height of the attachments is 30 ft. the total force is $42{,}200/30 = 1406$ lbs.

The breaking stress for western cedar or chestnut is from 5,000 to 6,000 lbs. per sq. in. and for Northern cedar 3,500 to 4,000 lbs. per sq. in.

For the normal unbalanced forces such as those due to an unguyed corner the fibre stress should not exceed about 15 per cent. of that at the breaking point, but for wind pressures and the unbalanced force due to broken wires which are abnormal and do not persist long, the stress is usually taken at about 50 per cent. of that at the breaking point. Hence the working fibre stresses for normal conditions may be taken at 800 lbs. per sq. in. for western cedar or chestnut and at 550 lbs. for northern cedar. For abnormal conditions a stress of 2,500 lbs. for western cedar or chestnut and 1,800 lbs. for northern cedar may be assumed.

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The above formula for allowable moment is based on the assumption that the ground line is at or near the weakest point of the pole. This is not always the case with northern cedar or other woods having a taper of 1 inch in 5 to 6 feet of length. The point of greatest fibre stress is that at which the diameter is 1.5 times the diameter at the point where the load is attached. That is with a pole having a diameter at the cross arm of 8 inches the greatest stress is at the point where the diameter is 12 inches. With a northern cedar pole this would be at a point $5\times(12-8)=20$ feet below the cross arms, and with the usual sizes of poles about 10 feet above ground.

When the point of maximum stress is above the ground line the allowable moment is determined from the formula

$$M=0.001781\ sc^2(c_1-c) \qquad (9)$$

in which c is the circumference at the point of attachment and c_1 is that at the point of maximum stress. It is usually found however that decay occurs at the ground line and as the age of the pole increases the ground line circumference is reduced to such a value as to make the ground line the point of greatest stress.

165. Example of calculation of pole size. Assume a Western cedar pole carries two cross arms, one of which carries a normal transverse pull of 400 lbs. at a height of 33 feet and the other 200 lbs. at 31 feet. What should be the ground-line circumference of the pole? $M=PL\times P_1L_1=400\times 33\times 200\times 31=19{,}400$ lb.-ft., and $19{,}400=0.0002638\times 800c^3$ whence $c^3=19{,}400/0.211$ and $c=\sqrt[3]{92{,}000}=45.2$ in. With a decrease of 3 inches in circumference for each 8 ft. in length the circumference at a point 32 feet above ground would be $(32/8)\times 3=12$ inches less than at the ground or $45.2-12=33.2$ in. This would require a pole having a top diameter of about 11 inches.

If the allowable fibre stress were increased to 2,500 lbs. instead of 800, as under storm conditions, the moment could be increased to $M=0.0002638\times 2.500c^3=60{,}700$ lb-ft.

If this were a Northern cedar pole the ground line circumference would be

$$c^3=\frac{19{,}400}{550\times .0002638}=133{,}600$$

$$c=\sqrt[3]{133{,}600}=51.2 \text{ in.}$$

With a decrease of 3 inches in circumference for each 5 ft. in length, the circumference at a point 32 ft. above ground would be $(32/5)\times 3=19.2$ in. less than at the ground.

$$c \text{ at top } =51.2-19.2=32 \text{ inches.}$$

166. Wind pressure. The design of pole lines to withstand wind pressure must be considered when they are in exposed positions. The pressure on flat surfaces normal to the direction of the wind may be calculated from the formula

$$P=0.004\ V^2 \qquad (10)$$

in which P is in lb. per sq. ft. and V is the velocity in miles per hour. For cylindrical surfaces such as wires and wood poles

$$P=0.0025\ V^2 \qquad (11)$$

In using the values of V taken from weather bureau reports it must be noted that the observed values are taken at elevations considerably above those at which wires are usually carried. The following correction* should therefore be made before using the bureau values in most cases.

Indicated velocity, miles per hour.	30	40	50	60	70	80	90	100
Actual velocity, miles per hour...	26	33	41	48	55	62	69	76

In closely built up districts in cities these "actual" values are still somewhat high. Where lines are in exceptionally exposed locations, as in passing over hills where there are no trees, the full indicated values may exist.

* Fowle, F. F. "A Study of Sleet Loads and Wind Velocities;" *Electrical World*, Vol. LVI, 1910, p. 995.

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The wind pressure on a 40-ft. pole, of which 34 ft. is above ground, with 7-in. top and 14-in. butt, would be calculated as follows. Projected area = $[(7+14)/2] \times 34 \times 12 = 4{,}284$ sq. in. = 29.75 sq. ft. Assuming a wind velocity of 60 miles per hr., $p = 0.002 \times (60)^2 = 7.2$ lb. per sq. ft. Total pressure on pole = $29.75 \times 7.2 = 214$ lb. This force acts at the centre of gravity of the projected area, which is a long narrow trapezoid; or 15.1 ft. from the ground-line. The moment of this force about the ground-line is therefore $214 \times 15.1 = 3{,}230$ lb-ft. Taking the diameter of No. 6 A.W.G. triple-braid weather-proof wire as 0.32 in., the total wind pressure at 60 miles per hr., on a 120-ft. span, would be 23 lb. and on twenty wires it would be 460 lb.; this resultant force would act at a point about 3 ft. below the top of the pole, or 31 ft. from the ground-line. The resulting moment would be 14,260 lb-ft. The sum of the wind pressures on pole and wires would be $3{,}230 + 14{,}260 = 17{,}490$ lb-ft.

167. Selection of poles. It is usual to select poles with 7-in. tops for important distributing lines.

The **height** of the poles selected for distribution purposes must be governed by the clearance over local obstructions and also by the number of cross-arms to be carried on the poles. Clearance over trees is especially troublesome in residence sections where trimming will not be permitted. In general it is desirable to use poles not less than 30 ft. long where primary lines are carried, and in built-up sections a minimum size of 35 ft. is preferable.

168. Poles for joint-line construction. Where joint-line construction with standard cross-arms is used, it is not usually possible to employ poles shorter than 35 ft. In a few cases the lines have been placed in cable and carried on 25-ft. poles on rear-lot lines. The use of poles over 40 ft. long is to be avoided wherever possible, on account of the cost, the increased danger in storms and the difficulty of handling transformers and service connections.

169. Poles should be spaced in approximately equal span lengths of about 100 ft. to 125 ft., to keep the sag within safe limits and to provide a sufficient number of points at which service drops may be taken off. The spans near self-supporting corner poles should be about 75 ft. long in order to relieve the strain on the corner pole. **The poles should be placed** opposite lot-lines to avoid interference with the rights of abutting-property owners.

170. Shaving and painting. It is considered good policy to carefully shave all poles, trim the knots, and give them two coats of paint. A dark green color is very commonly used because of its harmony with foliage in residence districts.

171. Stepping. Transformer poles and others which are climbed at frequent intervals should be provided with pole steps. It is the practice in many of the large city systems to provide steps on all poles.

172. Gaining. The gains should be cut for the cross-arms before the poles are erected. The **distance between cross-arm centres** must be sufficient to give clearance for service drops and allow a safe working space for linemen. The space usually allowed is about 24 in.

173. Pole setting. Experience has proven that the following practice is conservative, as regards the depth of setting.

Size pole (ft.)	30	35	40	45	50	55	60	70
Depth (ft.)	5	5.5	6	6.5	6.5	7	7	7.5

Corner poles should be set about 6 in. deeper than the above. In rocky soil where boulders may be tamped about the poles, they need not be set as deep.

The poles should be placed so as to bring their natural curvature into the plane of the line. At corners a **slight rake** may be given in a direction opposite to the pull of the load. Several tampers should be employed to

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one shoveler, in **back-filling**, in order to insure the stability of the pole. Water may be used to advantage, where available, in settling the back-fill. In swampy soil, the digging of holes is greatly facilitated by the use of a **sand-barrel**. This consists of a sheet-iron cylinder about 30 in. in diameter and 3 ft. long, which is separable into two parts lengthwise, and is readily removed after the pole is in place. Various methods of setting are shown in Fig. 47.

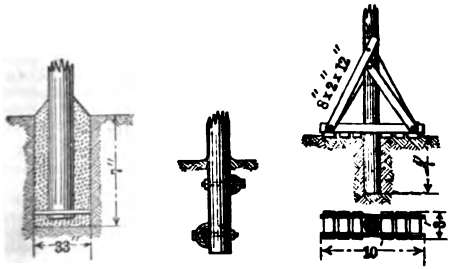


FIG. 47.—Methods of setting self-sustained poles.

174. Guying and bracing. Where the direction of a line changes, the tension of the wire should be supported by guying or bracing. The bracing method requires considerable space, and is more unsightly than a guy. Guys are secured in various ways, depending upon the space and the clearance required. Where nothing prevents, the guy cable may be secured to an **anchor** of timber or some form of patent anchor (Fig. 48). On public thoroughfares guys cannot be run directly to anchors without interfering with traffic, and the guys must be run to **stubs** at such height as to permit free passage of traffic beneath. Guys over roadways should clear about 25 ft., and those over pathways about 12 ft. (Fig. 48).

Where side-arm construction is used it is necessary at corners to guy the cross-arms as well as the poles. At heavy corners a "head" guy is run from the base of the corner pole to the upper part of the next pole in the line. The tension in the corner spans may thus be reduced, relieving the strain on the corner pole. In straight-away lines the head guy is used to limit the extent of damage in case several poles go down; this is sometimes called "storm guying."

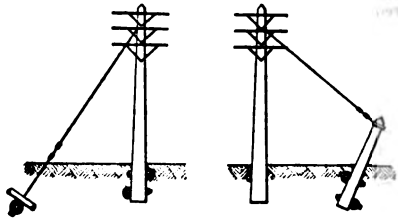


FIG. 48.—Anchor and stub guy.

175. Galvanized steel cable is generally employed for guying purposes because of its high tensile strength. Such cable is made in sizes varying in diameter by steps of $\frac{1}{16}$-in., from $\frac{1}{4}$-in. up. The **ultimate breaking strength of $\frac{1}{4}$-in. cable** is about 3,000 lb.; $\frac{5}{16}$-in., 4,500 lb.; $\frac{3}{8}$-in., 6,000 lb.; and $\frac{1}{2}$-in., 12,000 lb. Having calculated the tension, the size of guy cables should be such that the strain will be from one-fourth to one-fifth the ultimate breaking strength of the cable, or the **factor of safety of the steel cable**, from 4 to 5. Anchors should be placed at a distance from the pole not less than one-quarter the height of the guy attachment. In general, $\frac{1}{4}$-in. cable is used for the smaller loads, while the $\frac{3}{8}$-in. size is standard for corner poles where the load of the ordinary two-arm to three-arm distribution line is to be supported.

176. Strain insulators. It is important that guy cables attached to stubs be equipped with strain insulators not less than 8 ft. from the ground. This precaution is advisable for the protection of the public and of linemen.

177. Cross-arms. Southern pine and **Oregon fir** are the best woods for cross-arms because of their straight grain, high tensile strength, and

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durability. The **cross-section** should be such that the arm will safely bear the weight of a lineman in addition to that of the wires. Experience indi-

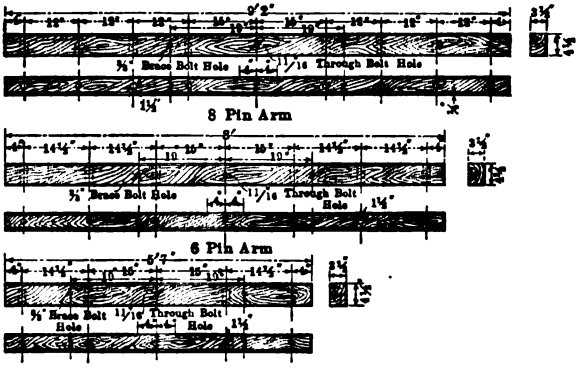


FIG. 49.—Dimensions of standard cross-arms.

cates that a cross-section 3.5 in. wide by 4.5 in. high is ample for the average requirements of distributing lines. For transformers of 20 kw. and larger it is usual to provide arms of a larger cross-section. Main lines are commonly built of six-pin arms, with four-pin arms on the smaller distributing lines. Where secondaries for both lighting and motor service must be carried on the same arm, it is usually necessary to employ six-pin arms.

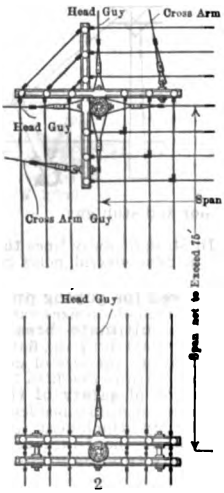


FIG. 50.—Reinforcement of corner poles by double cross-arms on adjacent poles.

The **spacing of pins** should provide safe working room for linemen and should take into account the average sag of the wires. Under the usual working conditions of distributing lines, it is not safe to attempt to use spacings less than 12 in. The spacing of the pole pins must give sufficient room for the men to climb to the upper arms, at least 30 in. being required for safety. The dimensions and spacings of standard cross-arms are shown in Fig. 49.

178. Double cross-arms. At corners, terminals, and other points where any unusual load is to be supported, the poles should be fitted with double arms. In turning corners on a single pole, the double-arming of both sets of arms makes the pole difficult of access to linemen. It is preferable, in case there are more than two cross-arms, to double-arm the first pole away from the corner in each direction, as shown in Fig. 50.

179. Cross-arm fittings. Cross-arms are fastened to the pole by **through-bolts** which

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should be ½ in. in diameter and from 12 in. to 16 in. long. The side on which the arm is attached is known as the **face of the pole.** **Cross-arm braces** are usually made of strap iron about ¼ in. by 1 in. and 26 in. to 30 in. long, and are attached to the pole by means of lag screws and to the cross-arms by stove bolts. For **side-arms** it is usual to use a brace of angle iron. This is rigid enough to bear the weight of a lineman on the step.

180. Cross-arm pins. **Wooden pins** are preferred for distribution work on account of their low cost and insulating qualities. Locust, elm, oak and some other woods are common, but locust is superior to all in strength and durability. **Iron pins** are commonly used for transmission lines where the size of the insulator necessitates a pin so long that wooden pins are not strong enough unless made undesirably large.

181. Insulators. The common type of insulator for distributing lines is that known as the **deep-groove double-petticoat** insulator, shown in Fig. 51. The dimensions are sufficient to carry 4,000-volt circuits safely. The point of support is low and the side strain on the pin is a minimum These insulators are made in glass and porcelain. The glass insulator is slightly less expensive than the porcelain in the deep-groove double-petticoat type, as is most commonly used. Some companies are using porcelain for primary wires and glass for secondaries, as a means of assisting linemen in the identification of circuits. Other porcelain types for higher voltages are also shown in Fig. 51.

182. Wire stringing. In erecting wire, the **tension** should be made sufficient to prevent too much sag in the spans, and yet not so great as to unduly

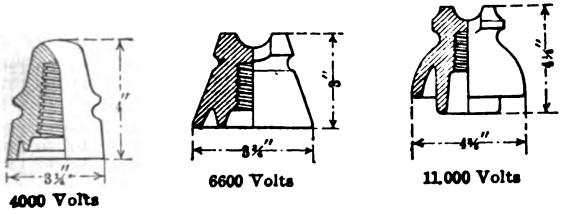


FIG. 51.—Standard types of insulators.

stress the wire. For practical purposes the approximate formula for sag and tension given by Rankine may be used:

$$T = \frac{L^2 w}{8S} \qquad \text{(lb.)} \qquad (12)$$

in which T is the tension in pounds, L is the span length in feet, w is the weight per foot of conductor and S is the sag in feet at the centre of a horizontal span. If the span length is doubled, the tension must be quadrupled in order to keep the sag the same. If the tension is the same on several spans of different lengths, the sag is different in each span. The sag of any span when the tension is known is found by changing Eq. 11 to the form, $s = L^2 w/8T$.

183. Sag tables. The maximum tension in a span is limited by the strength of the wire and supports. The ultimate breaking strength of annealed copper wire is about 34,000 lb. per sq. in., but the working stress should not be over one-fourth of this. The ultimate tensile strength of hard-drawn wire is about 60,000 lb. per sq. in. See Sec. 11 for a detailed treatment of sag and tension problems. The following table of sags for copper wire is taken from the **National Electrical Safety Code,** third (1920) edition.

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184. Sags for Hard and Medium-drawn Bare Copper Wire for Different Span Lengths

Heavy Loading Districts

(Sags are given in inches)

Size A.W.G. No.	Grade of construction	Temperature (deg. fahr.)	Length of span (ft.)								
			100	125	150	175	200	250	300	400	5
8	C.....	30	8	11.0	22.0	....	....	....	....	....	..
		60	12	18.0	27.0	....	....	....	....	....	..
		90	16	22.0	32.0	....	....	....	....	....	..
6	A.....	30	8	11.0	22.0	....	....	....	....	....	..
		60	12	18.0	27.0	....	....	....	....	....	..
		90	16	22.0	32.0	....	....	....	....	....	..
6	B.....	30	6	10.5	16.0	....	....	....	....	....	..
		60	10	15.0	22.0	....	....	....	....	....	..
		90	14	19.5	27.0	....	....	....	....	....	..
6	C.....	30	6	10.5	16.0	28	....	....	....	....	..
		60	10	15.0	22.0	33	....	....	....	....	..
		90	14	19.5	27.0	39	....	....	....	....	..
4	All.....	30	6	10.5	16.0	22	32.0	64	109	....	..
		60	10	15.0	21.0	28	38.0	71	115	....	..
		90	14	19.5	26.5	34	45.0	77	120	....	..
2	All.....	30	6	10.5	13.0	16	18.5	35	59	129	2
		60	10	15.0	18.0	21	24.0	44	68	137	2
		90	14	19.5	23.5	28	31.0	51	75	144	2
1	All.....	30	6	10.5	13.0	16	18.5	32	51	113	1
		60	10	15.0	18.0	21	24.0	40	59	120	2
		80	14	19.5	23.5	28	31.0	47	67	130	2
0	All.....	30	6	10.5	13.0	16	18.5	31	45	100	1
		60	10	15.0	18.0	21	24.0	38	55	110	1
		09	14	19.5	23.5	28	31.0	46	63	120	1
00	All.....	30	6	10.5	13.0	16	18.5	29	42	92	1
		60	10	15.0	18.0	21	24.0	36	50	102	1
		90	14	1915	23.5	28	31.0	44	58	111	1
0000	All.....	30	6	10.5	13.0	16	18.5	26	34	73	1
		60	10	15.0	18.0	21	24.0	32	42	84	1
		90	14	19.5	23.5	28	31.0	40	50	94	1

185. Discussion of sag table (Par. **184**). The values of sag in th foregoing table are the minimum values which are permissible witho danger of rupture under the loading conditions specified. Greater valu may be used where necessary to reduce strains, as at corners and turns, b increased separations may be required to prevent wires swinging together such cases. The blank spaces in the above table indicate these limits in general way, the values being omitted where the sag required for safety is t great to be used without increasing the separation of conductors.

The condition known as "heavy loading" is that existing when the wi is coated with ice having a radial thickness of ½ in. and is subjected to wind velocity of 8 lb. per square foot at a temperature of zero deg. fa Sag tables for medium and light loading districts will be found in the Natio Electrical Safety Code.

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The values in the table are not the theoretical values derived by formula, but include some allowance for flexibility of supports which experience has indicated is permissible.

In service the sag tends to increase causing "slack," which may become a hazard to the service if not taken up. This is caused by the permanent elongation of wire and by the movement of poles supported by guys which are not strictly rigid. Such a condition is common in the spring when the earth is softened by thawing. Elongation of the conductor is likely to be found in soft copper conductors after a few years of service.

186. Expansion and contraction of spans with temperature changes.* The changes in sag due to expansion and contraction under varying temperatures are of much importance in the erection of the conductors. Lines erected during the winter months are likely to be too slack during the summer, and allowance should be made accordingly. The length of wire in a span, disregarding the elastic stretching due to the load, varies in proportion to the coefficient of expansion and the range of temperature:

$$L_t = L_o(1 + \alpha_o t) \qquad (13)$$

in which α is the coefficient of expansion, t is the temperature in deg. fahr. and L_o is the length of wire at zero temperature. The linear coefficient of expansion of copper is 0.000017 per deg. cent. or 0.0000094 per deg. fahr.

In practice the pole supports have a certain degree of flexibility which tends to take up part of the slack caused by expansion and to prevent excessive strains being placed on the wires by contraction during cold weather.

187. Transformer installations. Transformers are usually supported on cross-arms by means of iron hangers. This class of construction is suitable for transformers of capacities up to 20 kw. For larger units the cross-arms should be double, and heavier than the standard arm. Large transformers which cannot be placed inside the building are often installed on a platform between two poles.

188. Overhead service connections. The connections to buildings by which consumers are served, called "services," are very numerous and represent a large fraction of the total cost of the overhead line system. The most common support consists of a "buck" arm on the pole and a malleable iron or steel bracket at the building. The buck arm provides ample pin space from which to support several services to different buildings.

Where the secondary main is carried on vertical racks the service arm is not required as the connection may be made directly at the rack. An extra rack is provided for the back side of the pole, if services are taken off on both sides of the line.

In some localities where buildings stand close together and are of uniform depth it is feasible to connect a row of buildings by one or two services, from the pole line, through distributing main attached to the rear walls of the group at a suitable height. The service is attached to the building at a height of 12 to 25 feet, the minimum height being governed by the desirable clearance from the ground and the maximum height by the accessibility to line construction men working from ladders.

The service is often extended in conduit directly from the point of attachment to the basement, in order to give greater accessibility to the service switch and meter.

189. Grounded secondaries. To protect life and property in case a primary circuit becomes crossed with a secondary, it is very important that the secondary be grounded. This is preferably done by connecting the secondary circuit to water pipes where these are accessible. Where the ground must be made outdoors, the most practicable method is to drive a galvanized iron pipe into the ground to a depth of about 8 ft. The points to be grounded in various kinds of secondary mains are indicated in Fig. 52.

190. The grounding of secondaries up to 150 volts has been required by the National Electrical Code since 1913. There is some doubt as to the advisability of grounding secondaries when the difference of potential between any wire and ground is higher than 250 volts, owing to the possibility that shocks from such a system may prove fatal.

* Thomas, P. H. "Sag Calculations for Suspended Wires;" *Trans.* Amer. Inst. of Elec. Eng.; Vol. XXX, 1911; p. 2229.

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191. When the ground connection is made to a pipe at the pole, the ground-wire is preferably brought down the pole in half-round wooden moulding. The ground wire may be soldered to the pipe about a foot above the ground, or may be attached by means of a pipe cap as shown in Fig. 53.

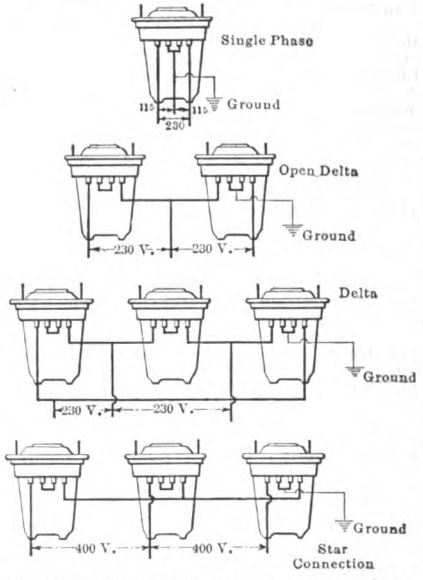


FIG. 52.—Connections for grounded secondary.

192. Arrangement of wires. The position of wires on the cross-arms should be assigned according to a systematic plan. Circuits should be kept on the same pins throughout their course, to facilitate maintenance work. In general, through lines should be carried on the upper arms and local distributing lines at the bottom. All the wires of a circuit should be carried on adjacent pins. Connections carried across the pole for transformers or service drops should leave one side of the pole free for climbing.

193. Joint occupancy of pole lines. The use of a joint line of poles is preferable to separate lines, on thoroughfares where there are many service drops, as it avoids much confusion. Where poles are occupied jointly by both electric-light and telephone companies, *the lighting wires should always occupy the upper position.* A clearance of about 4 ft. should be maintained between the lower lighting wires and the telephone wires. Joint-line construction is the rule in most of the larger cities. For details of recommended forms of joint-line construction, see the "Report of Committee on Overhead Line Construction," Trans. N. E. L. A., 1911.

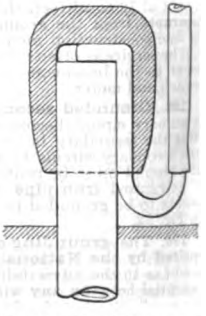


FIG. 53.—Ground-pipe cap.

UNDERGROUND CONSTRUCTION

194. Edison tube system. The underground system devised by Edison consisted of 20-ft. lengths of iron pipe inside of which were copper rods imbedded in compound to exclude moisture. These lengths were made with various sizes of conductor from No. 4 A.W.G. up to 500,000 cir. mils for mains and up to 1,000,000 cir. mils for feeders. Feeder tubes were provided with three pressure wires to indicate at the station the pressure at the end of the feeder.

195. Arrangement of Edison tube system. Edison tube is joined by stranded connectors enclosed in cast-iron couplings which are filled with hot compound. At intersections the tubes

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are interconnected through fused junction boxes. Such tube lines are carried along each side of the street near the curb except where consumers are scattered or where an alley is used. The Edison tube system was the standard method of distributing low-tension energy underground until about the year 1897. The change to cable was made on account of the inability of the tube feeders to carry overloads without causing burn-outs. The necessity of opening street pavements in each case where repairs were made, also involved considerable expense.

196. Conduit systems. The early alternating-current and series-arc systems which were installed underground were unable to use a system similar to the Edison tubes because of the higher voltages employed. They were compelled to devise a drawn-in conduit system with manholes for handling the cables. Creosoted wooden pump log was tried and was satisfactory for some classes of work, but was too short-lived and inflammable.

Other systems were devised in which the ducts were intended to provide insulation, but experience proved that it was not practicable to maintain such a system. This led to the development of methods in which the insulation was applied to the conductor and the conduit was of some durable fire-proof material.

197. Modern standard conduit systems. Various forms of duct were tried out, but the most suitable were found to be those of fire-proof material such as terra cotta and clay tile.

A conduit made entirely of concrete and known as **stone pipe** has been used to some extent instead of clay tile. This is made in 5-ft. lengths and jointed with metal ferrules to preserve the alignment, single duct only being used. The conduit is laid in concrete, making a solid and durable duct system. The concrete pipe is fragile, however, and the breakage is likely to be greater than with the tile duct, if not carefully handled.

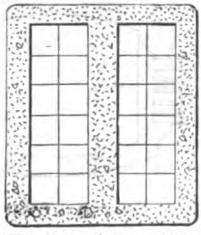


FIG. 54.—Arrangement of ducts for a large line.

Various forms of **fibre conduit** have also been used to some extent. These are laid with concrete around and between them, so that if the fibre disintegrates in after years there will remain a concrete duct system. The principal advantage is in the ease of handling and lack of breakage.

198. Laying out a conduit line. In the design of a draw-in duct system, the number of ducts, the size of manholes and their location are the important considerations. The number of ducts must be sufficient to care for the local distribution, for feeders, for transmission lines and for future requirements. It is desirable to lay sufficient reserve ducts to care for probable requirements for about 5 years ahead.

The **maximum number of ducts** which it is advisable to put into a line is governed chiefly by the safety of the cable equipment. The space available for training the cables is limited, and if more than twenty to twenty-five cables are carried through a manhole, a large part of the load is endangered by a failure of any of the cables. Where conditions are such that a very large line must be used, protection may be had by separating one-half of the duct line from the other by a 6-in. concrete barrier and by building double manholes. A line having more than four ducts in each layer is to be avoided where possible on account of the difficulty of properly training the cables. The arrangement shown in Fig. 54 is a desirable one where twelve or more ducts are laid.

199. Location of manholes. Manholes must be provided in sufficient number to permit the drawing in of cable without overstraining the insulation. Thus the **manhole spacing** should be not over 500 ft., with large cables, 400 ft. is a safer limit. Where distribution by overhead lines in alleys with under-ground lines on the street is used, manholes should be put opposite alley intersections as far as possible. The number of manholes required where numerous underground service connections are needed must usually be sufficient to enable services to be brought in at intervals of 25 ft. to 100 ft. In distribution by means of subway-type transformers and a secondary network, it is usually necessary to build extra large manholes for the transformers in order to get sufficient room and proper ventilation.

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Manholes should be so designed that the cables may be trained with a minimum of waste and with sufficient space to enable a jointer to work efficiently, as in the oval-shaped manhole shown in Fig. 55. At intersections a square design is preferable, as shown in Fig. 56. In practice it is usual to provide manholes 5 ft. by 5 ft. at **junctions** where there are eight ducts, that is, where two four-duct lines cross; 6 ft. by 6 ft. where there are twelve to eighteen ducts; 7 ft. by 7 ft. where there are twenty or more, and larger as the needs of the case may require.

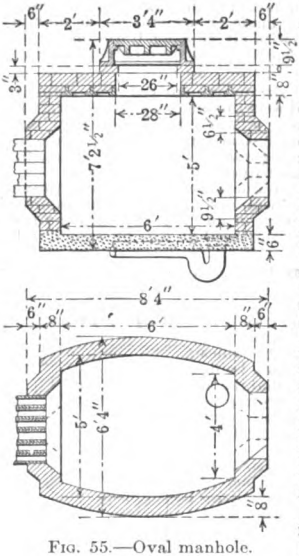


FIG. 55.—Oval manhole.

The size and the shape of manholes are often governed by local obstructions such as gas or water pipes, or conduit lines of other companies. The depth must be sufficient to give head room, and yet should not be so great as to carry the floor of the manhole below the sewer level. Service manholes may be 5 ft. high inside, but junction manholes should be 6 or 7 ft. from roof to floor. In some cases a shallow form of manhole known as a **handhole** is used for distribution laterals. These are made about 3 ft. by 4 ft., and 4 ft. deep. They are placed above the conduit line so that only the top row of ducts enters the handhole. The distributing mains are thus accessible for service taps, and the through lines in the lower ducts are not in the way.

200. Forms of duct. Tile conduit is made in single- and multiple-duct pieces, single-duct pieces being about 18 in. in length, and multiple-duct 36 in. long. The dimensions of ducts in general use are shown in Fig. 57. Multiple-duct is somewhat cheaper than an equal number of single

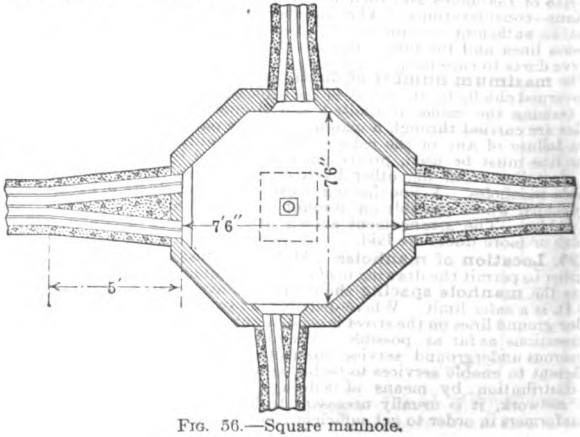


FIG. 56.—Square manhole.

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ducts and requires less labor. In a large system it is considered preferable to use single-duct to secure the advantage of having two thicknesses of tile between adjacent ducts. The single-duct also has the further advantage that the joints may be staggered, thus making it less likely that the heat of a burn-out may damage the cables in adjoining ducts.

201. Installation of conduit system. In laying a line of ducts the grades must be carefully established so that no pockets are formed where standing water may freeze and injure the insulation of the cables and break the tile. It is important that manholes where work must be done frequently, or where transformers or junction boxes are installed, be provided with sewer connections. The conduit line is protected from future excavators, and made secure against the possibility of getting out of alignment, by surrounding it with 3 in. of concrete on all sides. The con-

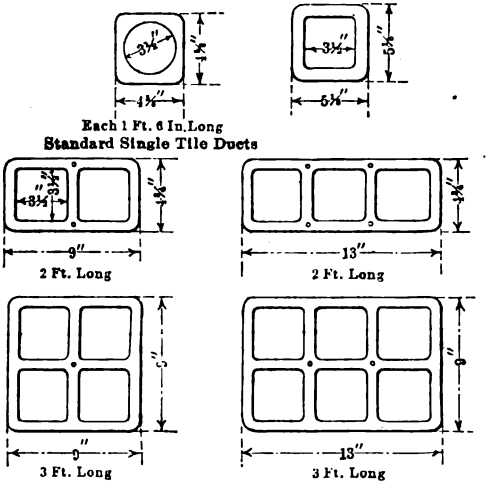


FIG. 57.—Forms of tile duct.

crete further acts as a water shed and minimizes the leakage of gas into the conduit system.

202. Manhole construction. The vaults or manholes provided to facilitate cable drawing and splicing are constructed of brick or concrete. In city streets where other underground structures interfere the walls are preferably built with sewer brick, only the floor and roof being of concrete. In building lines in open country, as for inter-urban telephone lines, forms are used and the entire vault may be advantageously constructed of concrete.

Brick walls should be 8 inches thick and laid up with a good quality of cement mortar. The floor should be connected to a sewer for drainage where it is available, except that in sandy soil the natural drainage is sometimes sufficient to prevent an accumulation of water in the vault. The roof of the vault must have sufficient strength to support the heaviest street traffic passing over it, which necessitates the use of steel reinforcement in most cases.

The manhole or entrance to the vault is covered by a cast iron cover having a roughened surface and of such strength as to bear the weight of trucks passing over it. Both circular and square covers are used, the circular cover having the advantage that it cannot fall into the vault in

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handling. Square or rectangular covers are preferred where low tension junction boxes and transformers are to be placed in the manholes.

Manhole covers are made single or double according to the service and local conditions. Single covers with openings for ventilation are preferred for conduit systems having power conductors, as this minimizes the danger from gas explosions. Double covers make it possible to have a lock on the manholes to prevent unauthorized entrance to the manhole. The inner cover is made lighter and if ventilation is not essential it may be provided with a gasket to keep the manhole free from surface water and dirt.

203. Cable supports should be provided for cables on the walls of the vault to prevent undue strain on the sheath and permit an orderly arrangement. This is sometimes done by arranging shelves of brick, or other suitable material but the shelf is usually only wide enough for one cable of the larger sizes, and this does not give sufficient room with the larger duct lines. It is, therefore, usual practice to provide racks of such a design as to permit two cables to be carried on each. In some forms the bracket on which the cable rests is detachable, and is not placed on the rack until a cable is to be installed.

204. Cost of Duct-lines per Duct-foot

No. of ducts	Cost of paving per square yard									
	None		1.50		3.00		4.50		6.00	
	1914	1920	1914	1920	1914	1920	1914	1920	1914	1920
2	0.40	1.25	0.55	1.40	0.70	1.55	0.85	1.70	1.00	2.15
4	0.23	0.70	0.31	0.78	0.38	0.85	0.46	0.93	0.53	1.00
6	0.21	0.64	0.27	0.70	0.32	0.75	0.37	0.80	0.45	0.86
9	0.19	0.59	0.24	0.64	0.28	0.68	0.32	0.68	0.37	0.77
12	0.18	0.55	0.22	0.59	0.26	0.63	0.30	0.67	0.34	0.71
16	0.17	0.52	0.20	0.55	0.24	0.59	0.28	0.63	0.31	0.66
20	0.17	0.50	0.19	0.52	0.22	0.55	0.24	0.57	0.27	0.60

205. Cost of manholes. The costs of certain sizes of manholes as built under conditions existing in the City of Chicago are given in the following table, in Par. **206**. The cost of paving is not included. The dimensions are those inside the manhole, the last being depth.

206. Cost of Manholes

	Unit costs		Quantities			
	1914	1920	3×3×4	4×5×5	5×5×6	6×6×6
Excavation, cu. yds...	$ 1.00	$ 3.00	3.7	7.8	16.3	19.0
Brickwork, cu. yds....	13.50	42.00	1.7	2.9	4.2	4.5
Concrete bottom, cu. yds.....	7.00	17.00	.....	0.4	0.6	0.7
Concrete top, cu. yds.	10.00	19.00	0.6	1.0	1.35	1.55
Roof iron, lbs.....	0.03	0.06	105.0	129.0	153.0	178.0
Frame and cover, each.	15.00	42.00	1.0	1.0	1.0	1.0
Sewer connection, each	20.00	45.00	1.0	1.0	1.0	1.0
Asphalt Paving, sq. yds.....	3.25	7.00	4.0	9.0	10.7	12.0
Total cost, 1914..	.....	.....	$ 64.15	$127.85	$165.20	$179.50
Total cost, 1920..	.....	.....	150.10	328.40	436.50	469.00

207. Types of cables. Cables for underground electric light and power circuits are made up in single, duplex, concentric, triplex, etc. Duplex and triplex cables are those in which two conductors are enclosed in one lead sheath side by side, while concentric cable is made up with the conductors concentrically disposed.

In general, single-conductor cable is used when frequent taps are required, as in distributing mains, while multiple-conductor cables are used for through

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lines. Duplex cable has been used quite extensively in series-arc systems. It is difficult to train, and susceptible to injury from bending at too small a radius. Duplex and triplex cables are somewhat less expensive than their equivalent in single-conductor cables with the same insulation.

The concentric arrangement is employed for large low-tension feeders in some cases. This arrangement is advantageous as it permits the use of a single duct for the feeder.

Low-tension distributing mains having three conductors of the same size are preferable of single-conductor cable, to facilitate making service taps. This work must be done while the lines are alive, and is much more easily accomplished when one polarity may be dealt with at a time. The same is true of service cables.

Transmission cables are almost universally of the three-conductor type. Insulation is placed on each conductor sufficient for the voltage between phases, and then a layer is placed over all three conductors in addition, as shown in Fig. 58, to provide insulation to ground.

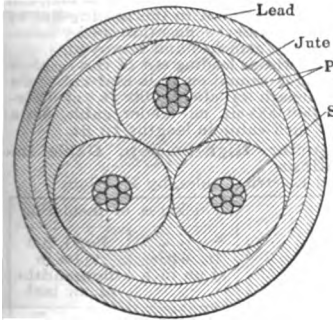


FIG. 58.—Cross-section of high-tension cable.

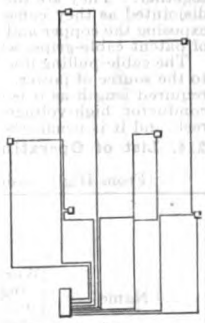


FIG. 59.—Lay-out of through cable lines to avoid the same routes.

208. Cable insulation. Cables are insulated with rubber, varnished cambric, or oiled paper. Rubber insulation is used where frequent taps are made, as on distributing mains, but not generally for feeders and transmission lines. Varnished cambric has been used to some extent in recent years as a substitute for rubber. Oiled paper is used almost exclusively for feeders and transmission lines, and can be used for primary distribution if the joints are well made and the ends are protected by suitable potheads.

209. Thickness of cable insulation. The smaller low-tension cables are provided with about $\frac{4}{32}$-in. insulation between conductors and lead; this is the least which it is advisable to use for mechanical reasons and is sufficient for 600 volts. In cables of 350,000 cir. mils to 1,500,000 cir. mils, it is customary to provide $\frac{5}{32}$ in. to $\frac{6}{32}$ in. of insulation, to insure sufficient mechanical strength to stand handling during installation. A thickness of $\frac{6}{32}$ in. is found sufficient for 2,000-volt to 6,000-volt single-conductor cables up to No. 4/0 A.W.G., while $\frac{10}{32}$-in. is required for potentials from 9,600 volts to 13,000 volts.

210. The insulation provided in transmission cables in large transmission systems varies from 66 mils per 1,000 volts between conductors, at 6,600 volts, to 22 mils at 25,000 volts; and from 52 mils per 1,000 volts between conductor and ground, at 6,600 volts, to 16 mils at 25,000 volts.

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211. Selection of duct position for cables. In placing cables in the duct-system a uniform method of selecting ducts should be followed as far as possible. Cables used in local distribution should be given a place, preferably in the top row, so that manholes can be built for service laterals without sinking them below the top row of ducts. Ducts should be selected for through lines so that they may be trained with the least interlacing with other cables. Lack of attention to this detail may result in a tangled condition of cables which greatly impedes any repair or reconstruction work.

212. Routing of cable lines. Through lines should be so routed as to utilize different duct lines to the best advantage. The service is better assured if transmission lines are separated as much as possible. This can be done by routing lines running to the same substation through different conduits, as indicated in Fig. 59.

213. Installation of cable. Cables are drawn into ducts by a line attached to a source of power. This line is put through the duct by the use of detachable rods of wood, which are pushed into the duct as they are joined together. They are then drawn through with the pulling-line attached, and disjointed as they come out. The cables are secured to the pulling-line by exposing the copper and making a secure mechanical connection, or by means of patent cable-grips, which are more quickly attached and removed.

The cable-pulling line is run over pulley-wheels leading out of the manhole to the source of power. Small-sized cable is wound on reels and cut to the required length as it is drawn in; but a length of about 400 ft. of three-conductor high-voltage cable, or of 1,000,000-cir. mil feeder cable, fills a reel, and it is usual, therefore, to order such cable in lengths to fit.

214. List of Operating Three-conductor, High-tension, Cable Installations

(From High-tension Underground Electric Cables, by H. Floy)

Name	Working voltage	Neutral grounded	Size of conductor B. & S. or C. M.	Insulation	Thickness of insulation			
					In 64ths of an inch		Per 1,000 volts in thousandths of an inch	
					About each conductor	Jacket	Between conductors	To ground
Brooklyn Rapid Transit Co.	6,600	No	250,000	Paper	13	10	61	54
New York Edison Company.	6,600	No	250,000	Paper	10	10	47	47
Cataract Power & Conduit Co.	11,000	No	000	Paper	13	13	37	37
Interborough Rapid Transit Co.	11,000	Yes	000	Paper	14	14	40	69
N. Y. C. & H. R. Rd.	11,000	Yes	0000	Paper	14	12	40	64
Minneapolis Rapid Transit Co.	13,000	Yes	3	Paper	12	12	29	50
Philadelphia Rapid Transit Co.	13,200	No	00	Paper	12	12	28	28
Baltimore United Railways.	13,200	Yes	000	Paper	14	10	33	49
Commonwealth Edison Co.	20,000	Yes	00	Paper	18	12	28	41
Detroit Edison Co.	23,000	Yes	2	Cambric	12	6	22	26
St. Paul Gas Light Co.	25,000	No	2	Paper	18	8	22	16
Shawinigan Power Co.	25,000	No	00	Rubber	28	none	17	17

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215. Training. The training of cable through manholes must avoid sharp bends, tangled relations with other cables and the possibility of injury by employes while working in the manhole. It is customary to support cables on iron racks hung on the walls. In some cases brickwork shelves are built around the walls, on which the cable is laid. It is usual to protect cables in manholes to prevent the communication of trouble to other cables. This is done by wrapping them with some fire-proofing material, or by the use of split tile. With large cables, the radius of bends should not be less than ten times the diameter of the cable. The shape of the manhole walls should be designed with this in view.

216. Jointing or splicing. In jointing single-conductor cables, the lead sheath is removed about 6 in. back from the end and enough insulation is cut away to permit a soldered connection to be made. When the connection is complete, the bare parts are wrapped with tape until the equivalent of the cable insulation has been applied. A lead sleeve which has previously been slipped back over one of the cables is now wiped on the two cable sheaths so as to enclose the joint. The air space around the joint is then filled with hot insulating compound poured into a small hole in one end of the sleeve; a similar hole is left open in the other end of the sleeve to allow air to escape. These holes are then closed by soldering. The joint should be allowed to cool before it is moved, so that the compound will hold the parts rigidly in place.

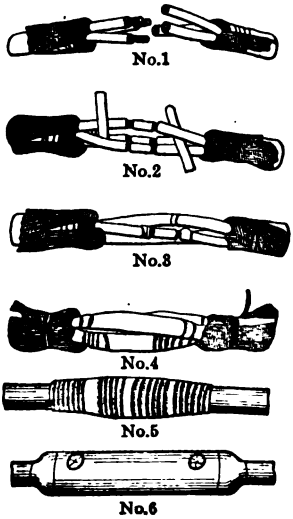


FIG. 60.—Cable splicing.

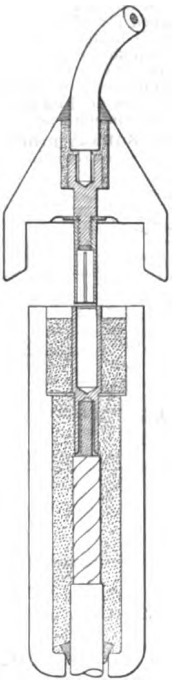


FIG. 61.—Porcelain pothead; single conductor type.

In jointing three-conductor cables, the lead must be removed about 10 in. to facilitate the taping of the conductors (Fig. 60). In making joints for voltages of 6,600 volts and higher, it is important that as little air remain in the taping as possible. If paper tape is used, each layer should have compound poured over it before the next is applied.

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The jointer requires the services of a helper in preparing the lead sleeves, heating solder and compound, and guarding the entrance to the manhole. A three-conductor high-tension joint in a paper cable usually requires about 4 hr. to complete, two joints a day being a fair rate of progress in such work.

217. Pole terminals. In many primary distributing systems, it is usual to run feeders and important mains underground for some distance from the station, and connect with overhead lines in the more scattered areas. This class of distribution requires that the cable ends which are brought up the pole to the overhead lines be properly protected by **cable terminals or potheads.** Various types of terminal are in use, some of which include means for connecting and disconnecting the overhead line. Many such distributing systems have been equipped with porcelain potheads which have been very successful in protecting cables. The first such device was designed for a single-conductor cable, as illustrated in Fig. 61. The insulation is hermetically sealed by filling the porcelain sleeve with compound. The cap sheds all water and may be safely handled by a lineman when the line is alive. The connectors provide means for readily opening and closing the circuit when necessary for repair or alteration work. Other forms have been devised for multiple-conductor cables, in which there is a pot of cast iron with porcelain tubes set into the cover (Fig. 62).

218. Subway junction boxes. The arrangement of junction boxes and similar accessories in manholes should be worked out so as not to obstruct the space needed for the cables. Low-tension junction boxes are of two types, one of which is mounted on the wall in a vertical position, while the other is placed in the roof of the manhole so that it is accessible for replacing fuses or cleaning contacts from above ground. The surface type has its advantages in districts where the drainage of manholes is not perfect.

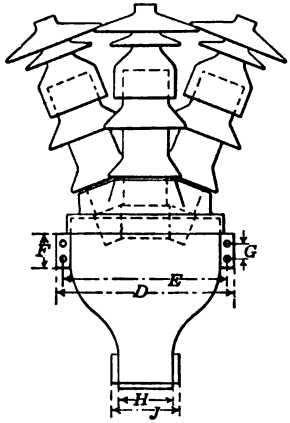


FIG. 62.—Cable pothead; triplex type.

219. Branch-line junction boxes. In a primary distributing system in which mains are underground, it is necessary to have means by which branches may be disconnected, without shutting down the circuit, when a transformer is to be connected or a cable repaired. Subway junction boxes with copper connections have commonly been applied to this work. The parts of the cable from which the lead has been removed are sealed in from moisture by wiped sleeves, or by filling the lower part of the box with hot compound. The **porcelain pothead** (Par. **220**) has also been found convenient for this purpose, in manholes, as the cap may be submerged without permitting water to reach the live parts.

DISTRIBUTION ECONOMICS

220. General criterion for most economical size of conductor. The loss of energy in a conductor diminishes as the size of the conductor is increased, and *vice versa*. The generating capacity required to supply the energy loss follows the same law. The size of conductor with which the sum of the fixed charges on conductor and generating capacity, plus the value of energy loss, is a minimum, is the one which it is the most economical to employ.

221. Fixed charges consist of interest, depreciation, taxes and insurance. These are computed at different rates, depending upon the character of the equipment. **Interest** should be figured at not less than the rate paid on the bonded debt, which is about 5 per cent. (Sec. 25).

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222. Depreciation is based upon the working life of the equipment, allowing for changes in the state of the art, and the scrap value of the equipment when taken out of service.

Weather-proof wire consists of about 80 per cent. copper and 20 per cent. insulation. It is conservative to figure 7 per cent. on the insulation, or 1½ per cent. of the whole wire, with 1 per cent. added for the labor of replacing, making a total of 2½ per cent. of the original cost of the wire. **Poles** have a life of about 15 years, with little salvage value. Other overhead **line material** must be replaced at intervals of 5 to 10 years. The average rate for **overhead lines** may thus be taken at about 5 per cent.

The life of lead-sheathed paper or rubber **cables** is indeterminate, but this may be conservatively taken at 15 years. The junk value is comparatively high, as the copper and the lead sheath constitute a considerable percentage of the cross-section of the cable. It is, therefore, safe to estimate depreciation at 3 per cent. for cables of No. 4/0 A.W.G. and larger, and at 5 per cent. for the smaller sizes.

223. Taxes and insurance must be considered as fixed charges of the same class as interest and depreciation. They vary somewhat with the locality, but are usually from 1.5 per cent. to 2 per cent., total.

224. The total fixed charges on underground cable and conduit may be taken at 5 per cent. interest, 4 per cent. depreciation, and 1 per cent. taxes, a total of 10 per cent. The total rate on the average overhead system may be taken at 5 per cent. interest, 5 per cent. depreciation, and 1 per cent. taxes, a total of 11 per cent.

225. General formula for annual conductor costs. The cost of a conductor varies inversely as its resistance per unit length, and the value of energy and generating capacity to supply it vary directly as the resistance per unit length. The total annual cost is

$$Y = \frac{a}{R} + bR + cR \qquad \text{(dollars)} \qquad (14)$$

in which a, b and c are constants depending on the cost of the conductor and the cost of energy. These are determined as follows: Par. **226** to **236**.

226. Formula for annual fixed charges on wire. The cost of insulation varies approximately with the size of the conductor. For bare wire the product of weight per 1,000 ft., W, by resistance per 1,000 ft., for all sizes, is $WR = 32$; with weather-proof insulation $WR = 38$ for the sizes No. 4 to No. 0 A.W.G., or 36 for sizes from No. 2/0 to 350,000 cir. mils. The value of 1,000 ft. of conductor at 15 cents per pound is $0.15W$ dollars. Hence, when $W = 38/R$, the cost per conductor of a circuit L thousand feet long is

$$C_1 = 0.15WL = \frac{0.15 \times 38L}{R} \qquad \text{(dollars)} \qquad (15)$$

Taking the fixed charges at 9 per cent., the annual cost is

$$C_1 = \frac{0.09 \times 0.15 \times 38L}{R} = \frac{0.513L}{R} \qquad \text{(dollars)} \qquad (16)$$

Thus $a = 0.513L$, in this case (Eq. 14).

227. Formula for annual fixed charges on single-conductor cable. With underground conductors a change in the size of the conductor does not make a proportionate change in cost. The table in Par. **229** gives the cost per 1,000 cir. mils of various sizes of single-conductor and three-conductor lead-sheathed cables. The resistance per 1,000 cir. mils per 1,000 ft. of copper at ordinary temperatures is about 10.4 ohms. If M is the number of 1,000 cir. mils and P is the price per 1,000 cir. mils, the cost of a single-conductor cable is MP. $M = 10.4/R$ and the cost of the cable is $10.4PL/R$, where L is the number of thousands of feet.

For **single-conductor low-tension cable** the value of P averages $1.20 for cables from No. 2/0 A.W.G. to 500,000 cir. mils, and the value of each conductor is

$$C_2 = \frac{10.4 \times 1.2L}{R} = \frac{12.48L}{R} \qquad \text{(dollars)} \qquad (17)$$

Taking the fixed charges at 9 per cent., the annual conductor cost is

$$C'_2 = \frac{0.09 \times 12.48L}{R} = \frac{1.12L}{R} \qquad \text{(dollars)} \qquad (18)$$

and in this case $a = 1.12L$ (Eq. 14).

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228. Formula for annual fixed charges on three-conductor cable. In the case of three-conductor cables the cost per 1,000 cir. mils in Par. 229 is based on the total cross-section of the three conductors. The cost of three-conductor cable is

$$C_3 = \frac{3 \times 10.4PL}{R} \quad \text{(dollars)} \quad (19)$$

and the annual charges are

$$C'_3 = \frac{0.09 \times 3 \times 10.4PL}{R} = \frac{2.8PL}{R} \quad \text{(dollars)} \quad (20)$$

and $a = 2.8PL$. Thus the value of a may be derived for different kinds of cable and at various values of copper, lead and insulation. Where a circuit is composed of more than one cable, this must be taken into account in figuring the total annual cost for the circuit; that is, for a two-wire circuit the value of "a" is doubled and for three cables it is trebled.

229. Cost of Lead-sheathed Cables

Size conductor A.W.G. or cir. mils	Cost per 1,000 cir. mils per 1,000 ft.			
	Single-cond. 3,000 volts	Three-cond. 10,000 volts	Single-cond. 300 volts	Three-cond. 300 volts
No. 2	2.20	2.80	1.90	1.85
No. 0	2.00	2.00	1.80	1.60
No. 00	1.70	1.85	1.60	1.50
No. 000	1.55	1.65	1.40	1.40
No. 0000	1.45	1.50	1.30	1.30
Cir. mils				
250,000	1.30	1.40	1.25	1.25
350,000	1.20	.....	1.10	.....
500,000	.....	.....	1.00	.....
750,000	.....	.....	0.90	.....
1,000,000	.....	.....	0.80	.....
1,500,000	.....	.....	0.75	.....

230. Fixed charges on generating equipment. Where conditions are such that generator capacity could be released for commercial load by the use of larger conductors, the fixed charges on generating equipment should be considered one of the elements of annual cost of a circuit. The station capacity required to supply the energy loss at the time of the maximum load I is $I^2RL/1{,}000$, in kw. The value of station capacity required to supply the loss on a feeder, when the cost is $100 per kw., is

$$C_4 = \frac{100 \times I^2RL}{1{,}000} \quad (21)$$

and the fixed charges per conductor at 12 per cent., are

$$C'_4 = 0.12 \times 0.1I^2RL = 0\ 012I^2RL \quad \text{(dollars)}$$

and $b = 0.012I^2L$ (Eq. 14).

231. Energy loss. The loss of energy on a circuit during a year is dependent upon the annual load factor of the load carried. In Fig. 63 typical load curves are shown for a lighting feeder which carries some day motor-load, for the months of March, June, September, and December. The energy losses will evidently be different on this feeder each month in the year, being less during the summer months than during the winter months.

The annual loss on a circuit may be computed with sufficient accuracy for practical purposes as follows: Take an average day in March, and compute the value of I^2R for each hour. Repeat this operation for the June, September and December curves. Multiply the sum of the losses on the four curves by 91, this being the number of days in each quarter of the year. This total is the annual loss in kilowatt-hours.

232. Loss factor. The ratio of the loss as thus calculated, to the value of the loss if the feeder had carried the maximum load of the year every hour of the year, may be called the loss factor, just as the ratio of the actual out-

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put for the year, to the possible output at the rate of the maximum load, is called the load factor of a circuit. If the loss factor of the feeder is 20 per cent., the annual loss is

$$\frac{I^2R\times 0.2\times 365\times 24}{1{,}000} = 1.752I^2R \quad \text{(kw-hr.)} \qquad (22)$$

The loss factor for a load having the characteristics illustrated in Fig. 63 is about 16 per cent.

233. Calculation of loss. Given the character of the load curve, the loss factor may be determined in the manner described (Par. **231** and **232**) and the annual loss of energy calculated from the maximum load I, in terms of R, the resistance per 1,000 ft. of conductor. The loss at the time of the annual maximum load being I^2RL, the annual loss is

$$\frac{I^2RL\times 8{,}760\times F}{1{,}000} \quad \text{(kw-hr.)} \qquad (23)$$

where F is the loss factor. The loss equals $1.40I^2RL$ kw-hr. when the loss factor is 16 per cent. The value of this energy may be taken at about 1 cent per kw-hr. in the smaller plants, 0.7 cent in the larger engine-driven plants and 0.5 to 0.3 cent in the turbine-driven plants. At 1 cent. per kw-hr. the value of the annual energy loss per conductor, at 16 per cent. loss factor, is

$$C_6 = 0.0140I^2RL \quad \text{(dollars)} \qquad (24)$$

and the constant c is equal to $0.0140I^2L$.

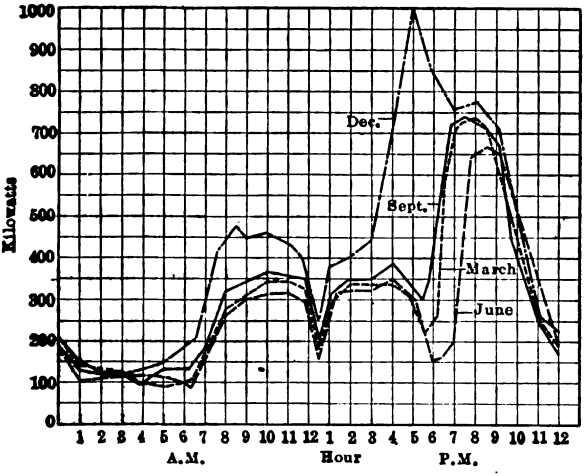


FIG. 63.—Typical load curves.

234. Summary of annual conductor costs; condition for minimum. The total annual cost is, therefore, the sum of the three quantities a/R, bR, and cR (Eq. 14). For weather-proof wire, with station capacity at $100 per kw., a loss factor of 16 per cent., and energy at 1 cent per kw-hr., the annual cost is

$$Y = \frac{a}{R} + bR + cR = \frac{0.513L}{R} + 0.012I^2RL$$

$$+ 0.014I^2RL = \frac{0.513L}{R} + 0.026I^2RL \quad \text{(dollars)} \qquad (25)$$

It is desired to ascertain at what value of R the sum of these three elements will be a minimum for a given current, at the time of the annual maximum

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load. The only variable in the equation being R, the value of Y will be a minimum, according to the rule of the calculus, when $\partial Y/\partial R = 0$.

If $Y = \frac{0.513L}{R} + 0.026I^2RL$, then $\frac{\partial Y}{\partial R} = \frac{0.026I^2R^2L - 0.513L}{R^2} = 0$. Therefore, $0.026I^2R^2L = 0.513L$, and $I^2R^2 = 0.513/0.026 = 19.7$; whence $IR = \sqrt{19.7} = 4.44$. For instance, if $I = 100$ amp., $R = 0.0444$ ohm, which is about the resistance per 1,000 ft. of a No. 4/0 conductor.

235. Examples of calculation of most economical size of conductor. Assume generating capacity costing $80 per kw., energy at 0.4 cent per kw-hr. and the loss factor at 25 per cent. With single-conductor low-tension cable of 500,000 cir. mils to 1,000,000 cir. mils, the cost per 1,000 cir. mils averages 90 cents per 1,000 ft., **Par. 229.**

Hence $\frac{a}{R} = \frac{0.09 \times 10.4 \times 0.9L}{R} = \frac{0.84L}{R}$,

$$bR = \frac{80 \times 0.12I^2RL}{1{,}000} = 0.0096I^2RL,$$

$$cR = \frac{0.004 \times 8{,}760 \times 0.25I^2RL}{1{,}000} = 0.0087\ I^2RL.$$

$$Y = \frac{84\ L}{R} + 0.0183I^2RL.$$

and $IR = \sqrt{\frac{0.84}{0.0183}} = \sqrt{46} = 6.7$ per 1,000 ft. of conductor. With 600 amperes $R = \frac{6.7}{600} = 0.011$, which is about the resistance of 1,000 ft. of 1,000,000-cir. mil cable.

In the case of three-conductor, 10,000-volt cables, with generating capacity costing $80 per kw., energy at 0.4 cent per kw-hr., loss factor at 25 per cent. and the cost of No. 0 cable $1.75 per 1,000 cir. mils,

$$aR = \frac{\$2 \times 0.09 \times 10.4L}{R} = \frac{1.87}{R} \text{ per conductor.}$$

$(b+c)R = 0.0183\ C^2RL$ per conductor. Therefore

$CR = \sqrt{\frac{1.87}{0.0183}} = 1.01$ and for 100 amp. $R = \frac{1.01}{100} = 0.101$ which is nearest the resistance of No. 0 cable, per 1,000 ft.

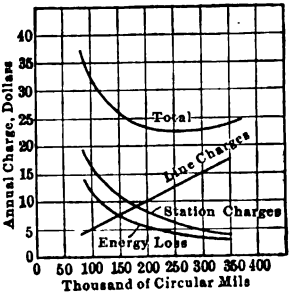


FIG. 64.—Elements of annual cost of a circuit.

236. The curves in Fig. 64 show the line charges, station capacity charges and line losses for various sizes of conductor, assuming a current of 100 amp., with overhead lines, energy at 1 cent. per kw-hr., cost of generating capacity at $125 per kw. of capacity, and loss factor 12 per cent.

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SECTION 13

INTERIOR WIRING

BY TERRELL CROFT

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SECTION 13

INTERIOR WIRING

RELATION OF WIRING TO FIRE RISK

1. The National Electrical Code was drawn originally in 1897. It was the product of the efforts of the National Conference on Standard Electrical Rules. This comprised delegates from the various insurance, electrical, architectural and allied interests of the United States. The object of the conference was to formulate a set of rules for the installation and construction of electrical apparatus *in a manner free from fire hazard*. The *National Electrical Code* resulted. The "*Code*" was immediately adopted by the National Board of Fire Underwriters, 135 William St., New York City. It at once placed electric wiring on a safe basis. At present practically all wiring is in accordance with *Code* rules. The fire insurance policies in some states and communities expressly provide that the *Code* shall be followed in detail. The National Conference on Standard Electrical Rules has disbanded but the work of the Underwriters' National Electrical Association and the National Conference has been taken over by the National Fire Protection Association, in which are represented the following organizations: American Electric Railway Association; American Institute of Electrical Engineers; Associated Factory Mutual Fire Insurance Cos.; National Board of Fire Underwriters; National Electric Light Association; National Electrical Contractors Association; National Electrical Inspectors Association.

Periodically the National Fire Protection Association convenes and authorizes such revisions or additions to the *Code* as are dictated by advances in the art. The *National Electrical Code* is revised every 2 years. A supplement and a "*List of Approved Fittings*," are issued semi-annually. Either can be obtained gratis on application to any Underwriters'-Association office, to any local inspection bureau, or to The National Board of Fire Underwriters, 135 William St., New York City.

2. Legal status of the Code. The *Code* has no statutory force. It merely comprises the rules of the National Board of Fire Underwriters. However, certain cities have passed ordinances providing that all work installed in such cities shall be in accordance with the *Code*. This gives it a legal status in these cities. Moreover, other cities have legalised requirements of their own, which are, usually, essentially *Code* requirements. Where local requirements are authorized by ordinance or statute they, of course, take precedence over the *Code* rules.

3. Electric Service Company Rules are often enforced by local electric-power companies. These may relate to location and details of service entrances, provisions for meters, minimum voltage drop allowable in circuits and similar matters. The electric service company supplies free copies of such rules.

4. The National Code rules of are great economic importance in relation to fire hazard and fire insurance. Without question, fire loss amounting to many thousands of dollars has been averted by their application. When installing any electrical equipment, first ascertain whether there are local installation rules (ordinances) in force in the community. If there are such they should be followed. If there are none follow the *National Electrical Code* rules.

5. Inspection.—Every electrical installation should be inspected, whenever an experienced inspector is available, to insure that it complies with either local or *Code* rules. In cities where rules have been adopted by ordinance, such inspection is usually mandatory. Where inspection is not mandatory, it is always advisable to retain an inspector from the most convenient Underwriters' Bureau to examine the work while it is being installed. Nominal fees are charged for such inspection.

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6. All fittings and materials used in wiring installations should be approved by the Underwriters Laboratories. Practically all standard equipment now being marketed is so approved and, usually, is so marked. When in doubt one should refer to the "*List of Approved Fittings*" referred to above, or consult The Underwriters' Laboratories, 207 East Ohio St., Chicago, Ill.

METHODS OF WIRING

7. There are eight methods of wiring. (1) open or surface wiring; (2) concealed knob and tube wiring; (3) wooden-raceway wiring; (4) metal-wiring; (5) flexible-tubing or circular-loom wiring; (6) rigid iron-conduit wiring; (7) flexible metallic conduit wiring; (8) flexible steel-armored cable wiring.

8. Open wiring on knobs and cleats (Fig. 1) is a cheap and satisfactory method if installed in compliance with *Code* requirements. It is largely used in industrial plants and in mercantile establishments where appearance is unimportant. Single-braid, rubber-covered or slow-burning weather-proof wire may be used. Wires having slow-burning insulation must not be used in damp places. The wires must be supported at least every 4.5 ft. (137 cm.) except in buildings of "mill" construction where, if "not liable to be disturbed," they may be supported at every beam, provided that the wires are No. 8 or larger and are carried at least 6 in. (15.2 cm.) apart. In dry places for voltages up to 300, the wires must be separated at least

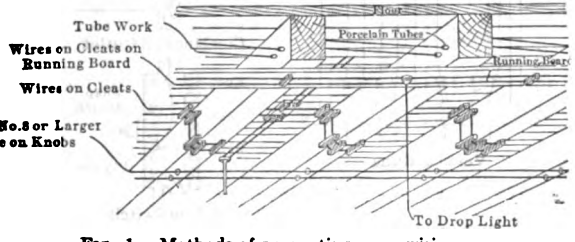


FIG. 1.—Methods of supporting open wiring.

2½ in. (6.35 cm.), and they must be at least 0.5 in. (1.27 cm.) from the surface wired over. For voltages between 301 and 600, wires must be at least 1 in. (2.54 cm.) from the surface and must be separated 4 in. (10.2 cm.). In damp places, for voltages up to 300, wires must be held 1 in. (2.54 cm.) from the surface; above 300 they should be 4 in. (10.2 cm.) from the surface. Where wires are exposed to mechanical injury, protection must be afforded as specified by the *Code*. Wires must also be protected by porcelain tubes where they pass through walls, timbers or partitions. See the *National Electrical Code* for other minor requirements.

In structural-steel mill-type buildings, open wiring is carried on porcelain knobs or cleats which may be secured with stove bolts at points where there are spaces between the members or where holes are already punched. Sometimes it is desirable to screw the cleats to blocks which are clamped to the members with hook bolts.

Open work is especially suited to locations which are damp or hot such as dye works, breweries, dry kilns, metal refineries and the like. In such installations special precautions must be observed; these precautions are fully described in treatises on wiring.

9. Knob-and-tube wiring (Fig. 2) is used in frame buildings, and is the cheapest method of concealed wiring. Although it has given satisfaction, it is in progressive communities being superseded by rigid conduit. In some cities only rigid iron or flexible conduit or flexible steel-armored cable is approved for concealed work.

The single-braid, rubber-insulated conductors are carried within the floors, walls and partitions of the building. Where passing through timbers they must be insulated with porcelain tubes. On a vertical run the wires

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must be protected from plaster droppings by tubes which extend at least 4 in. (10.2 cm.) above the horizontal timbers which have been pierced.

Within partitions and floors, where the wires are carried on knobs, the knobs must be spaced not more than 4.5 ft. (1.37 m.); the wires should be spaced at least 5 in. (12.7 cm.) and should be carried on separate timbers. They

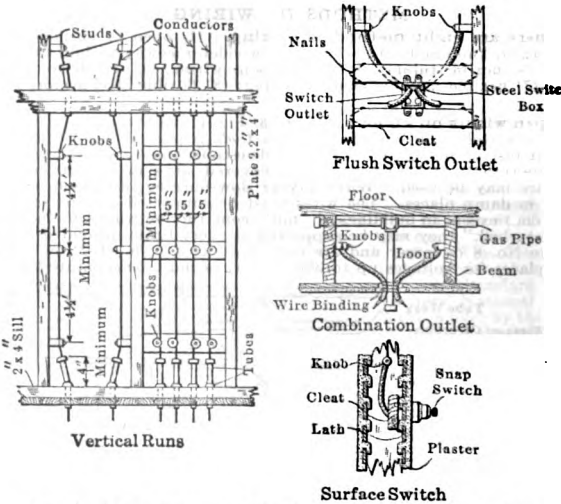


FIG. 2.—Typical details of knob and tube method of wiring.

may be closer together if encased in flexible tubing. Only split knobs should be used for conductors smaller than No. 8; either split or tie knobs may be used for larger conductors. The wires must have the same insulation as the wires they support, and must not be smaller than No. 14. Flexible tubing must be used to protect conductors at each outlet, and must extend from the last point of support into the outlet box in one continuous length. Sheet-steel boxes must be used for flush-switch outlets as shown in Fig. 2.

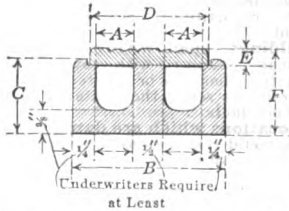


FIG. 3.—Standard, two-wire, wooden raceway.

10. Wooden raceway is, as a rule, used only for making additions to existing installations where good appearance is a consideration but where running the conductors concealed is either impossible or economically prohibitive. Wooden raceway wiring is now prohibited by ordinance in many communities. Wooden raceway wiring is not approved for damp places or where the difference of potential between any two wires of the same system exceeds 300 volts. Single-braid rubber-covered wire is required. No joints or splices are permitted except at outlets and at fittings. There are many styles of approved moulding fittings. With them almost any conceivable combination of connections can be realized.

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11. Dimensions and capacities of wooden raceways. Below are given the dimensions of standard two-wire wooden raceways; the products of various manufacturers vary somewhat. All dimensions are given in inches (Fig. 3). (Kirkpatrick Mfg. Co.)

A Size of groove	Will accommodate wires		B	C	D	E	F
	Solid	Stranded					
0.250	14 to 12	.....	$1\frac{1}{2}$	$\frac{5}{8}$	$1\frac{1}{8}$	$\frac{3}{16}$	$\frac{13}{16}$
0.375	10 to 8	8	$1\frac{1}{2}$	$\frac{5}{8}$	$1\frac{3}{8}$	$\frac{3}{16}$	$\frac{13}{16}$
0.500	9 to 4	5 to 6	$2\frac{1}{8}$	1	$1\frac{3}{8}$	$\frac{3}{32}$	1
0.625	3 to 0	4 to 1	$2\frac{1}{2}$	$1\frac{3}{16}$	$1\frac{5}{8}$	$\frac{7}{32}$	$1\frac{1}{8}$
0.750	.....	0 to $\frac{1}{0}$	$2\frac{7}{8}$	$1\frac{1}{4}$	$2\frac{3}{16}$	$\frac{1}{4}$	$1\frac{3}{8}$
0.875	.....	$\frac{1}{0}$ to 250,000	$3\frac{1}{8}$	$1\frac{3}{8}$	$2\frac{7}{16}$	$\frac{1}{4}$	$1\frac{1}{4}$
1.000	.....	250,000 to 500,000	$3\frac{5}{8}$	$1\frac{5}{8}$	$2\frac{13}{16}$	$\frac{1}{4}$	$1\frac{7}{8}$

12. Metal raceway (formerly termed "Metal Moulding") can be used only for exposed circuits. It is now largely employed, in the place of wooden raceway (Par. **10**). It also finds application in new construction in commercial buildings and in industrial plants, being substituted for open wiring. This raceway occupies little space (see Fig. 4), is very neat in appearance and being sherardized, will take paint readily. The conductors in the raceway can be readily removed for inspection at any time. Alterations in or additions to the raceway system can be very easily and neatly made. Fittings are manufactured, whereby almost any possible wiring arrangement can be effected. See *National Electrical Code* and manufacturers' catalogues for further information. Metal-raceway wiring costs somewhat less than conduit and, for exposed work, provides a neater appearance. It can be

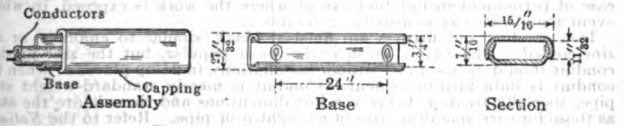


FIG. 4.—National metal raceway.

used only where the potential difference does not exceed 300 volts and the power 1,320 watts. It must be continuous from outlet to outlet or to approved fittings. It should not be used in damp places.

Single-braid, rubber-insulated wire can be used in metal raceway. Wires must be laid in—not fished. The raceway shown in Fig. 4 has a capacity of four No. 14 wires. All wires of an alternating current circuit must be in the same raceway, and it will be found advantageous to treat direct-current circuits likewise.

13. Flexible tubing (**circular loom, duraduct, etc.**) is now seldom used except in combination with other methods of wiring. However, it is very useful and finds wide application for furnishing additional insulation and protection to conductors. It cannot be used in damp places. See *National Electrical Code* for further information. Where metal outlet boxes or switch boxes are used, flexible tubing must extend from the last porcelain support into the outlet box. It is used for encasing wires fished between walls and ceilings, each wire being separately encased. It is also used in open work where wires, are nearer each other than 2.5 in.; on wires crossing other wires, gas pipes, water pipes, iron beams, wood work, brick or stone; on wires at chandeliers and bracket outlets; on gas pipe back of insulating joints; on wires under the edges of canopies: Where space is limited and the 5-in. separation required between wires cannot be maintained, each wire must be separately encased in a continuous length of flexible tubing. Flexible tubing may also be employed as an added protection to wires; as for instance on portable wires around machinery and in show windows, etc., where added protection, although not required, is often desirable.

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14. Typical Dimensions of Flexible Tubing (Circular Loom)

Below are given the dimensions of one standard line of flexible tubing, or circular loom, which has been approved by the Underwriters' Laboratories.

Inside diam., inches	Outside diam., inches	Ft. per coil	Largest wire, A.W.G., and cir. mils	Weight per 1,000 ft.-lb.
$\frac{1}{4}$	$\frac{17}{64}$	250	No. 14	75
$\frac{3}{8}$	$\frac{25}{64}$	250	No. 12	110
$\frac{1}{2}$	$\frac{33}{64}$	200	No. 8	125
$\frac{5}{8}$	$\frac{41}{64}$	200	No. 4	155
$\frac{3}{4}$	$1\frac{1}{16}$	150	No. 2	200
1	$1\frac{3}{8}$	100	No. 00	275
$1\frac{1}{4}$	$1\frac{13}{16}$	100	200,000	360
$1\frac{1}{2}$	$2\frac{1}{16}$	100	400,000	400
$1\frac{3}{4}$	$2\frac{1}{2}$	100	600,000	440
2	$2\frac{3}{4}$	Odd lengths	800,000	600
$2\frac{1}{4}$	3	Odd lengths	1,100,000	700
$2\frac{1}{2}$	$3\frac{1}{4}$	Odd lengths	1,300,000	700

15. Rigid iron conduit wiring (Par. **16**, **17** and **19**) is approved for both exposed and concealed work in practically all classes of buildings. It provides the safest and most satisfactory method of electric wiring yet developed. Though highest in first cost of all of the methods it is probably the most economical for permanent installations. In the most progressive cities, only rigid or flexible iron conduit or steel-armored cable is permitted for concealed work. Rigid iron conduit should have the preference in every case of permanent installation except where the work is exposed, in which event metal raceway is usually preferable.

Iron conduit and fittings are finished black, similar to enamel, or are zinc-coated. The black finish is the most popular, but the zinc-finished conduit should be used for outdoor installations, in damp places or when the conduit is imbedded in cement. Conduit is merely standard-weight steel pipe, specially treated; hence conduit dimensions and threads are the same as those for corresponding sizes of wrought-iron pipe. Refer to the *National Electrical Code* for complete rules for conduit installations.

16. Iron conduit fittings. Outlet and switch boxes, elbows, supports, hangers and other conduit fittings are manufactured in almost endless variety, and can be procured to meet practically any condition. See manufacturers' catalogues and the *National Electrical Code*.

17. Wire for use in iron conduit must except in permanently dry places, be rubber-insulated. Where No. 6 or equivalent or larger, double-braided wire must be employed. Where smaller than No. 6, single-braided wire is permitted. Each conductor must be continuous (without splices) from outlet to outlet. For alternating-current circuits, all the wires of one circuit must be carried in the same conduit to eliminate heating and excessive voltage drop due to electromagnetic induction. Varnished-cloth insulation may be used in permanently-dry locations. Slow-burning insulation wire may be used in permanently-dry locations where the temperature is excessively high, if special permission is secured.

18. Flexible metallic conduit (Fig. 5) is approved for the wiring of practically all classes of buildings. It is used principally for wiring finished buildings, in cities where iron conduit is required, or where a thorough job is desired. It is used for wiring near machinery, and in other locations where the conduit run changes direction frequently, or where the wires must be fished. It is also useful in wiring new frame buildings because it can be easily bent in any direction; however, rigid conduit is cheaper and more frequently used for this service. It can be installed more readily than can rigid conduit, which is manufactured in lengths of 10 ft. Flexible



FIG. 5.—Greenfield flexible-steel conduit.

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metallic conduit is furnished in coils of from 25 to 250 ft., depending upon the conduit size. The wire and the general installation requirements are practically the same as for rigid conduit. Many fittings for flexible metallic conduit are manufactured, although no elbows are required.

19. Electrical Trade Size of Conduits for the Installation of Wires and Cables

(1920 *National Electrical Code*)

Table 1. Two-wire and Three-wire Systems

Size of conductor, B. & S. gage	Number of conductors in one conduit								
	1	2	3	4	5	6	7	8	9
	Minimum size of conduit in inches								
14	½	½	½	¾	¾	1	1	1	1
12	½	½	¾	¾	¾	1	1	1	1¼
10	½	¾	¾	1	1	1	1¼	1¼	1¼
8	½	¾	1	1	1	1¼	1¼	1¼	1¼
6	½	1	1¼	1¼	1½	1½	2	2	2
5	¾	1¼	1¼	1¼	1½	2	2	2	2
4	¾	1¼	1½	1½	2	2	2	2	2½
3	¾	1¼	1¼	1½	2	2	2	2½	2½
2	¾	1¼	1½	1½	2	2	2½	2½	2½
1	1	1½	1½	2	2	2½	2½	3	3
0	1	1½	2	2	2½	2½	3	3	3
00	1	2	2	2½	2½	3	3	3	3½
000	1	2	2	2½	3	3	3	3½	3½
0000	1¼	2	2½	2½	3	3	3½	3½	4
Cir. mils									
200,000	1¼	2	2½	3	3	3	3½	3½	4
225,000	1¼	2½	2½	3	3	3½	3½	4	4
250,000	1¼	2½	2½	3	3	3½	3½	4	4½
300,000	1¼	2½	3	3	3½	3½	4	4½	4½
350,000	1¼	2½	3	3½	3½	4	4½	4½	5
400,000	1¼	3	3	3½	4	4	4½	5	5
450,000	1½	3	3	3½	4	4½	4½	5	6
500,000	1½	3	3	3½	4	4½	5	5	6
550,000	1½	3	3½	4	4½	5	5	6	6
600,000	2	3	3½	4	4½	5	6	6	6
650,000	2	3½	3½	4	4½	5	6	6	6
700,000	2	3½	3½	4½	5	5	6	6	.....
750,000	2	3½	3½	4½	5	6	6	6	.....
800,000	2	3½	4	4½	5	6	6	6	.....
850,000	2	3½	4	4½	5	6	6	.....	.....
900,000	2	3½	4	4½	5	6	6	.....	.....
950,000	2	4	4	5	6	6	6	.....	.....
1,000,000	2	4	4	5	6	6	.....	.....	.....
1,100,000	2½	4	4½	6	6	.....	.....	.....	.....
1,200,000	2½	4½	4½	6	6	.....	.....	.....	.....
1,250,005	2½	4½	4½	6	6	.....	.....	.....	.....
1,300,000	2½	4½	5	6	6	.....	.....	.....	.....
1,400,000	2½	4½	5	6	.....	.....	.....	.....	.....
1,500,000	2½	4½	5	6	.....	.....	.....	.....	.....
1,600,000	2½	5	5	6	.....	.....	.....	.....	.....
1,700,000	3	5	5	6	.....	.....	.....	.....	.....
1,750,000	3	5	5	6	.....	.....	.....	.....	.....
1,800,000	3	5	6	6	.....	.....	.....	.....	.....
1,900,000	3	5	6	.....	.....	.....	.....	.....	.....
2,000,000	3	5	6	.....	.....	.....	.....	.....	.....

For sizes not greater than No. 10 A. W. G. gage, one more conductor than permitted by the above table may be installed in the specified conduit, provided the conduit is not longer than 30 feet, and has not more than the equivalent of two quarter bends from outlet to outlet, the bends at the outlets not being counted.

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20. Flexible steel-armored conductor (Fig. 6) has found considerable application during the last few years, due to its adaptability for electrical construction in finished buildings. It can be run with practically no regard for pipes or other grounded obstructions and can be fished for relatively-long distances. It is more expensive than conductors in circular loom but it provides a thoroughly dependable job. Flexible steel-armored conductor consists of rubber-insulated wire or cable, protected from injury and to some extent from dampness by two layers of spirally wound flexible steel armor. It is manufactured "*leaded*" and "*unleaded.*" The leaded conductor has a lead sheath (between the armor and the cloth covering which is wound over the rubber) to exclude dampness. Both types are made in any reasonable gage of wire or cable. The leaded type is approved for use in all classes of buildings and can be installed during or after their construction. The unleaded type is approved only for use in locations that will not be permanently damp.

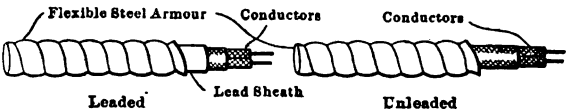


FIG. 6.—Flexible steel-armored conductor.

21. Relative Costs of Various Methods of Wiring
(Based on Values in "Electric Light Wiring," C. E. Knox)

Method of wiring	Relative cost in per cent.
Conduit (rigid iron)	100
Raceway or Moulding (metal)	80
Flexible metallic conduit	80
Flexible steel-armored cable	70
Raceway or Moulding (soft wood)	50
Open wiring (knob and cleat)	40
Flexible tubing or Circular Loom (now obsolete)	40
Concealed knob and tube	35

The values given are approximate for average conditions. They include all labor and material for "roughing in" but do not include lamps, fixtures, switches or accessories.

WIRES AND CABLES

22. Electric wire and cable terminology. (*U. S. Bureau of Standards Circular No.* 37.)

Wire. A slender rod or filament of drawn metal. The definition restricts the term to what would ordinarily be understood by the term "solid wire." If a wire is covered with insulation, it is properly called an insulated wire; in general the term "wire" will be understood to include the insulation.

Conductor. A wire or combination of wires not insulated from one another, suitable for carrying a single electric current.

Stranded Conductor. A conductor composed of a group of wires or any combination of groups of wires. The wires in a stranded conductor are usually twisted or braided together.

Cable. (1) A stranded conductor (single-conductor cable); or (2) a combination of conductors insulated from one another (multiple-conductor cable). The component conductors of the second kind of cable may be either solid or stranded, and this kind of cable may or may not have a common insulating covering. A small cable is called a "stranded wire" or a "cord," both of which are defined below. Cables may be bare or insulated, and the latter may be armored with lead or with steel wires or bands.

Strand. One of the wires or groups of wires of any stranded conductor.

Stranded wire. A group of small wires, used as a single wire. A wire has been defined as a slender rod or filament of drawn metal. If such a filament is subdivided into several smaller filaments or strands, and is used

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as a single wire, it is called "stranded wire." There is no sharp dividing line of size between a "stranded wire" and a "cable." If substantially insulated, it is called a "cord," defined below.

Cord. A small cable, very flexible and substantially insulated to withstand wear. Usually the insulation of a cord contains rubber.

Concentric strand. A strand composed of a central core surrounded by one or more layers of helically laid wires or groups of wires.

Concentric-lay cable. A single-conductor cable composed of a central core surrounded by one or more layers of helically laid wires.

Rope-lay cable. A single-conductor cable composed of a central core surrounded by one or more layers of helically laid groups of wires. This kind of cable differs from the preceding in that the main strands are themselves stranded.

N-conductor cable. A combination of N conductors insulated from one another. (It is not intended that the name as here given be actually used. One would instead speak of a "3-conductor cable," a "12-conductor cable," etc. In referring to the general case, one may speak of a "multiple-conductor cable," as in definition for "*Cable*" above.)

N-conductor concentric cable. A cable composed of an insulated central conducting core with tubular stranded conductors laid over it concentrically and separated by layers of insulation. Usually only 2-conductor or 3-conductor. Such conductors are used in carrying alternating currents. The remark on the expression "N-conductor" given for the preceding definition applies here also.

Duplex cable. Two insulated single-conductor cables twisted together. They may or may not have a common insulating covering.

Twin cable. Two insulated single-conductor cables laid parallel, having a common covering.

Triplex cable. Three insulated single-conductor cables twisted together. They may or may not have a common insulating covering.

Twisted pair. Two small insulated conductors twisted together, without a common covering. The two conductors of a "twisted pair" are usually substantially insulated, so that the combination is a special case of a "cord."

Twin wire. Two small insulated conductors laid parallel, having a common covering.

23. Specifications for insulated conductors are given in detail in the *Standard for Rubber-covered Wires and Cables* which is issued and revised periodically by the Underwriters' Laboratories. Since these specifications are subject to revision, it is inadvisable to repeat them here. Practically all rubber-insulated wire on the market is manufactured in accordance with *Code* requirements. To each coil is fastened a tag indicating the approval of the Underwriters' Laboratories. Unapproved wire should not be installed.

24. Current-carrying capacity of copper wires. If the current carried by a given conductor is too great, the conductor will become so hot that it will be unsafe, or may, if insulated, damage its insulation. Certain safe current values have been determined for different sizes of conductor, and are listed in Par. **27**. Less current is permissible in rubber-insulated wires than in wires insulated with other materials because relatively low temperatures may injure rubber insulation. For interior wiring, the capacities recommended by the *National Electrical Code* in Par. **27** should not be exceeded unless contrary local municipal ratings are mandatory.

25. Allowable current-carrying capacities of aluminum wire are 84 per cent. of the values given in the table for copper wire (Par. **27**), assuming the same kind of insulation.

26. Rubber-covered or rubber-insulated wires and cables (Par. **30**, **31**, and **32**) when protected with one braid over the insulation, are known as single-braid wires. When two braids are used to afford additional protection against injury by abrasion, they are known as double-braid wires. Rubber-insulated conductors must be used for all **concealed** inside wiring and for all wiring in damp places. They must be used throughout where the voltage exceeds 600. Conductors insulated with less expensive materials (see following paragraphs) can be used out-of-doors on pole lines and inside in dry places where the wires are exposed. The *National Electrical Code* permits single-braid, rubber-covered wires for exposed interior wiring in damp places and in raceways. See Par. **17** for requirements for conduit wire.

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27. Allowable or Safe Current-carrying Capacities of Insulated Copper Wires

(1920 *National Electrical Code*)

B. & S. gage	Diameter of solid wires in mils	Area in circular mils	Table A rubber insulation, amperes	Table B varnished cloth insulation, amperes	Table C other insulation, amperes
18	40.3	1,624	3	.....	5
16	50.8	2,583	6	.....	10
14	64.1	4,107	15	18	20
12	80.8	6,530	20	25	25
10	101.9	10,380	25	30	30
8	128.5	16,510	35	40	50
6	162.0	26,250	50	60	70
5	181.9	33,100	55	65	80
4	204.3	41,740	70	85	90
3	229.4	52,630	80	95	100
2	257.6	66,370	90	110	125
1	289.3	83,690	100	120	150
0	325	105,500	125	150	200
00	364.8	133,100	159	180	225
000	409.6	167,800	175	210	275
		200,000	200	240	300
0000	460.	211,600	225	270	325
		250,000	250	300	350
		300,000	275	330	400
		350,000	300	360	450
		400,000	325	390	500
		500,000	400	480	600
		600,000	450	540	680
		700,000	500	600	760
		800,000	550	660	850
		900,000	600	720	920
		1,000,000	650	780	1,000
		1,100,000	690	830	1,080
		1,200,000	730	880	1,150
		1,300,000	770	920	1,220
		1,400,000	810	970	1,290
		1,500,000	850	1,020	1,360
		1,600,000	890	1,070	1,430
		1,700,000	930	1,120	1,490
		1,800,000	970	1,160	1,550
		1,900,000	1,010	1,210	1,610
		2,000,000	1,050	1,260	1,670

28. Weather-proof wire or cable (Par. **33**) is used for out-of-door conductors and should be supported on porcelain or glass insulators and not on knobs, cleats or rubber hooks. Weather-proof *Code* wire is not approved for inside wiring except where exposed to corrosive vapors. The so-called "weather-proof" insulation becomes a reasonably good conductor when moist. Triple-braid weather-proof conductors have three braids, saturated with a so-called moisture-proof compound, served around them, and double-braid conductors have two such braids. Triple-braid weather-proof conductors are approved by the *National Electrical Code* for outside construction, but double-braid conductors are not approved at all.

29. Slow-burning conductors are insulated with three braids impregnated with a fire-resisting compound, as is used on slow-burning weather-proof conductors. The *Code* approves slow-burning conductors for interior exposed wiring, in dry places, where the voltage does not exceed 600. They are particularly applicable for hot, dry places where ordinary insulations would soon perish. The outer braid is finished like that of slow-burning weather-proof conductors, and has the same properties. See table Par. **33**.

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30. Dimensions and Weights of Rubber-insulated Wires and Cables. National Electrical Code Standard, 0-600 Volts
(Standard Underground Cable Co.)

A.W.G.	Conductor area cir. mils	Dia. bare wire mils	Rubber insulation 64th in.	Solid wire				Stranded or cable			
				Single braid		Double braid		Single braid		Double braid	
				Dia. mils	Lb. per 1,000 ft	Dia. mils	Lb. per 1,000 ft.	Dia. mils	Lb. per 1,000 ft.	Dia. mils	Lb. per 1,000 ft.
18	1,624	40	2	143	14.5	185.0	19.1	.....	.....	.....	.....
16	2,582	51	2	155	18.9	197.0	23.9	.....	.....	.....	.....
14	4,106	64	3	208	33.0	258.0	40.0	216.0	34.3	268	42.4
12	6,530	81	3	225	43.1	275.0	51.5	235.0	44.9	285	53.8
10	10,381	102	3	246	58.1	296.0	67.2	260.0	60.6	310	70.1
9	13,094	114	3	258	68.4	308.0	78.2	274.0	70.0	324	80.0
8	16,509	128	3	273	82.1	322.0	92.2	290.0	85.5	340	96.3
6	26,251	162	4	337	130.0	387.0	142.0	360.0	136.0	410	149.0
5	33,102	182	4	357	154.0	407.0	167.0	396.0	166.0	460	184.0
4	41,742	204	4	393	190.0	457.0	208.0	422.0	198.0	486	218.0
3	52,634	229	4	418	228.0	482.0	247.0	451.0	238.0	515	260.0
2	66,373	258	4	447	276.0	511.0	297.0	504.0	293.0	588	324.0
1	83,694	289	5	530	363.0	614.0	395.0	571.0	377.0	655	412.0
0	105,593	325	5	565	439.0	649.0	474.0	613.0	457.0	697	494.0
00	133,100	365	5	605	528.0	689.0	564.0	659.0	556.0	743	595.0
000	167,805	410	5	650	646.0	734.0	685.0	709.0	675.0	793	719.0
0000	211,600	460	5	700	793.0	784.0	835.0	767.0	833.0	851	879.0
.....	250,000	575	6	.....	.....	.....	.....	845.0	997.0	929	1,047.0
.....	300,000	630	6	.....	.....	.....	.....	902.0	1,173.0	986	1,226.0
.....	400,000	729	6	.....	.....	.....	.....	1,001.0	1,514.0	1,085	1,573.0
.....	500,000	815	6	.....	.....	.....	.....	1,087.0	1,842.0	1,171	1,906.0
.....	600,000	893	7	.....	.....	.....	.....	1,194.0	2,220.0	1,278	2,290.0
.....	700,000	964	7	.....	.....	.....	.....	1,266.0	2,557.0	1,350	2,631.0
.....	800,000	1,031	7	.....	.....	.....	.....	1,333.0	2,891.0	1,417	2,968.0
.....	1,000,000	1,152	7	.....	.....	.....	.....	1,455.0	3,553.0	1,539	3,637.0
.....	1,500,000	1,413	8	.....	.....	.....	.....	1,747.0	5,344.0	1,831	5,445.0

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31. Dimensions and Weights of Rubber-covered Wires and Cables for Voltages from 600 to 1,500

Size A.W.G.	Size Cir. mils	No. of wires in cond.	Diam. of wires comprising cable, mils.	Thickness of rubber in inches	Diameter over all: Single braid Mils	Single braid 64ths	Double braid Mils	Double braid 64ths	Approx. weight per 1,000 ft., tape and braid
Solid									
14	4,107	....	.....	1/64	239	15.3	289	18.5	46
12	6,530	....	.....	1/64	256	16.4	306	19.6	58
10	10,380	....	.....	1/64	277	17.75	327	20.9	75
8	16,510	....	.....	1/32	304	19.45	354	22.6	100
6	26,250	....	.....	1/32	382	24.2	446	28.5	153
4	41,740	....	.....	1/32	425	27.2	489	31.3	212
2	66,370	....	.....	1/32	498	31.9	582	37.2	310
1	83,690	....	.....	1/32	561	35.9	645	41.25	394
Stranded									
1	83,690	19	66.4	1/32	604	38.65	688	44.0	405
0	105,500	19	74.5	1/32	645	41.25	729	46.6	490
00	133,100	19	83.7	1/32	691	44.25	775	49.6	595
000	167,800	19	94.0	1/32	742	47.5	826	52.8	715
0000	121,600	19	105.5	1/32	800	51 2	884	56.5	875
.....	400,000	37	104.0	7/64	1,032	66.0	1,116	71.4	1,570
.....	600,000	61	99.2	1/8	1,227	78.5	1,311	83.9	2,300

32. Dimensions and Weights of Rubber-covered Wires and Cables for Voltages from 1,500 to 2,500

Solid									
12	6,530	....	.....	1/32	318	20.4	368	23.55	85
10	10,380	....	.....	1/32	339	21.7	389	24.9	100
8	16,510	....	.....	1/32	380	24.3	444	28.4	130
6	26,250	....	.....	1/32	414	26.5	478	30.6	175
4	41,740	....	.....	1/32	456	29.2	520	33.3	240
2	66,370	....	.....	1/32	509	32.6	573	36.65	330
1	83,690	....	.....	7/64	592	37.0	676	43.25	420
Stranded									
8	16,510	7	48.6	1/32	398	25.5	462	29.6	140
6	26,250	7	61.2	1/32	436	27.9	500	32.0	185
4	41,740	7	77.2	1/32	504	32.25	588	37.6	250
2	66,370	7	97.4	1/32	564	36.1	648	41.5	340
1	83,690	19	66.4	7/64	635	40.6	719	46.0	435
0	105,500	19	74.5	7/64	676	43.25	760	48.6	520

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33. Dimensions and Weights of Weather-proof and Slow-burning Insulation Solid Copper Wire and Cable

(General Electric Co.)

Size A.W.G. and cir. mils	Weather-proof: Approx. wts. per 1,000 ft. (lb.)		Weather-proof: Approx. overall diameters, in.		Slow-burning: Approx. weights per 1,000 ft. (lb.)			Slow-burning: Approx. overall diameters, in.			A.W.G. and cir. mils.
	Triple braid	Double braid	Triple braid	Double braid	Weather-proof white finish	Weather-proof black finish	Under-writers	Weather-proof or white	Weather-proof or black	Under-writers	
Solid wire											
1	310	290	0.445	0.405	350	340	330	0.445	0.445	0.445	1
2	255	232	0.400	0.374	290	280	280	0.400	0.400	0.400	2
4	164	146	0.346	0.320	200	190	180	0.346	0.346	0.346	4
6	112	97	0.303	0.278	140	127	125	0.303	0.303	0.303	6
8	75	64	0.264	0.245	95	85	90	0.264	0.264	0.264	8
10	53	46	0.221	0.197	70	60	65	0.221	0.221	0.221	10
12	35	27	0.200	0.172	52	42	40	0.200	0.200	0.200	12
14	25	20	0.182	0.155	40	30	30	0.182	0.182	0.182	14
16	19	15	0.169	0.142	30	24	22	0.169	0.169	0.169	16
Stranded											
1,000,000	3,478	3,360	1.451	1.365	3,880	3,980	3,578	1.451	1.451	1.451	1,000,000
750,000	2,615	2,551	1.300	1.210	3,020	3,100	2,720	1.300	1.300	1.300	750,000
600,000	2,113	2,060	1.190	1.105	2,370	2,460	2,204	1.190	1.190	1.190	600,000
500,000	1,781	1,740	1.108	1.027	2,010	2,080	1,858	1.108	1.108	1.108	500,000
400,000	1,445	1,405	1.020	0.940	1,670	1,700	1,509	1.020	1.020	1.020	400,000
300,000	1,126	1,090	0.930	0.846	1,290	1,310	1,170	0.930	0.930	0.930	300,000
250,000	937	905	0.862	0.780	1,080	1,120	981	0.862	0.862	0.862	250,000
0,000	806	753	0.785	0.708	910	960	844	0.785	0.785	0.785	0,000
000	655	610	0.728	0.648	745	785	686	0.728	0.728	0.728	000
00	515	470	0.662	0.599	590	625	550	0.662	0.662	0.662	00
0	420	382	0.605	0.555	485	510	449	0.605	0.605	0.605	0
1	328	300	0.518	0.470	360	380	360	0.518	0.518	0.518	1
2	267	251	0.440	0.415	300	335	294	0.440	0.440	0.440	2
4	173	153	0.379	0.353	205	230	196	0.379	0.379	0.379	4
6	117	103	0.327	0.305	145	165	135	0.327	0.327	0.327	6
8	75	69	0.290	0.270	97	105	94	0.290	0.290	0.290	8

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34. Slow-burning weather-proof conductors (Par. **33**) are sometimes used for interior exposed wiring in damp places, where there are corrosive vapors, provided that the voltage does not exceed 600. They are cheaper than rubber-insulated conductors. The insulation consists of an inner weather-proof coating and an outer fire-resisting coating. The Code requires that the fire-resisting coating be $\frac{1}{16}$ the thickness of the entire coating. To meet this condition the manufacturers use one weather-proof braid and two fire-resisting braids. The fire-resisting compound consists of a mixture containing white lead, oxide of zinc, chalk, or some similar substance. The outer braid is rubbed smooth on the outside. The manufacture of slow-burning weather-proof conductors has been discontinued by some manufacturers and they are now seldom used. Slow-burning weather-proof wire is cheaper than slow-burning wire. It is not suitable for out-of-door service. Wires with a fire-resisting outer coating have the advantage that dust and lint do not adhere readily to their outer surfaces, as is often the case with weather-proofed braids. If dust does collect, it can be easily swept off.

35. Weather-proof, slow-burning conductors have a fire-resisting coating next to the conductor and a weather-proof coating on the outside. They are not approved by the *Code*.

36. Twin wires or cables (Par. **37**) (sometimes called "conduit wires") are used where they are to be drawn into conduit and should never be used except in conduit or in metal raceways. Each wire is rubber insulated to the thickness indicated in Par. **30**, and then is served with a braid or with a tape. The two conductors are finally bound together parallel one with another, with a tenacious braid at least 0.0312 in. thick for wires larger than No. 10 B. & S. gage and 0.0125 in. for No. 10 B. & S. gage or less in size. This construction is considered by the Underwriters' Laboratories as equivalent to that of double-braid, rubber-covered wire. Twin conductors larger than No. 0000 should not be used because of their tendency to kink.

37. Dimensions and Weights of National Electrical Code-Stranded, Twin (Flat) Wire and Cable, 0-600 Volts

(*General Electric Co.*)

Size of each conductor A.W.G.	Solid			Stranded		
	Weight in lb. per 1,000 ft.	Dimensions in in.		Weight in lb. per 1,000 ft.	Dimensions in in.	
		Thickness	Width		Thickness	Width
8	214	0.33×0.57		214	0.35×0.61	
10	162	0.26×0.48		162	0.32×0.51	
12	126	0.28×0.44		126	0.29×0.48	
14	100	0.22×0.40		100	0.23×0.42	

38. Fibre-cored cables (Par. **39**). Alternating current flowing in large cables has greater density on the surface of the conductor than in the center (so-called skin effect). Therefore an ordinary cable will not carry as great an alternating current as a direct current, with the same temperature rise. To compensate for this it is advisable, for single-conductor cables 700,000 cm. and larger for 60-cycle circuits, and 1,250,000 cm. and larger for 25-cycle circuits, to strand the copper around a non-conducting fibre core. The weight of copper in a cable of this type is the same per ft. as in a copper cable without a core, but owing to its annular cross-section the cored cable is much more efficient in alternating-current circuits and also has a somewhat greater current-carrying capacity due to the larger radiating surface. The copper strands can be covered with any desired type of insulation.

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39. Dimensions and Current-carrying Capacities of Fibre-cored Cables. (*General Electric Co.*)

Size cir. mils	Dia. fiber core, in.	No. of wires in strand	Size wire in strand, in.	Overall dia. copper core, in.	Ampere capacity	
					30 deg. cent. rise	60 deg. cent. rise
2,000,000	0.875	210	0.099	2.065	1,400	1,750
1,750,000	0.780	210	0.091	1.87	1,300	1,625
1,500,000	0.687	182	0.091	1.78	1,200	1,500
1,250,000	0.562	168	0.086	1.59	1,150	1,400
1,000,000	0.469	98	0.102	1.28	900	1,150
800,000	0.344	51	0.125	1.1	775	925
750,000	0.312	48	0.125	1.060	750	900
700,000	0.281	51	0.117	0.99	700	830
500,000	0.250	45	0.1056	0.890	550	660

40. Conductors with varnished cambric or oiled-cloth insulation are not recommended for wires smaller than No. 6. The insulation consists of cloth which is impregnated with oil, dried and then wound spirally around the conductor to the required thickness. A braid or some other form of protection is served around the outside. Such conductors are largely used for voltages exceeding 2,400, but for lower voltages rubber insulation appears to be the best suited, and is used much more extensively than any other. The varnished cloth insulation has a tendency to unwind; this affords no trouble to wiremen who are familiar with its manipulation, but may cause the uninitiated some inconvenience.

FITTINGS AND ACCESSORIES

41. Snap switches. Surface snap switches and flush snap switches are made for practically any service, and are procurable in certain designs for voltages as high as 600. These include single-pole, double-pole and triple-pole switches; three-way or four-way switches, for the control of hall lamps from any one of several locations; and the electrolier switches. They can be obtained (for 250 volts) for currents as large as 30 amp. Snap switches are usually preferable to knife switches from an operating standpoint as any one can operate them, under normal conditions, without drawing a destructive arc. Indicating switches, which show by their appearance whether they are open or closed, should preferably be used. Flush snap switches are installed in pressed-steel switch boxes which are set in walls or

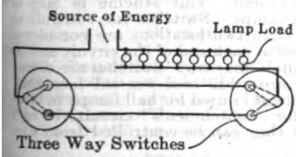


FIG. 7.—Control of circuit from two locations with three-way switches.

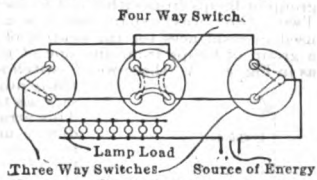
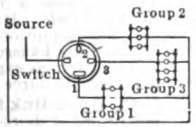
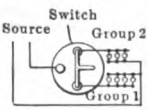


FIG. 8.—Control of circuit from any one of more than two locations.



Three-Circuit Switch



Two-Circuit Switch

FIG. 9.—Wiring for electrolier switches.

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partitions, so that only the plate and operating buttons are visible. Types can be obtained which will furnish practically the same service as surface snap switches. Those of the flush type are more expensive but present a neater appearance than surface switches.

42. Electrolier switches (Fig. 9) control lamps in independent groups such as would be used in an illuminated dome or electrolier. Switches are made for this service in the "flush," "surface" and "pull" types. Operation of the two-circuit switch is as follows: Position *A*, all lamps off; *B*, only those of group 1 are on; *C*, both groups on; *D*, only those of group 2 are on. With the next movement all lamps are extinguished. The sequence outlined is typical, but all electrolier switches do not provide just this sequence. A three-circuit switch is necessary for controlling three groups. With one type, the sequence for the different positions is as follows: *A*, connects group 1; *B*, connects groups 1 and 2; *C*, connects groups 1, 2, and 3; *D*, disconnects all lamps.

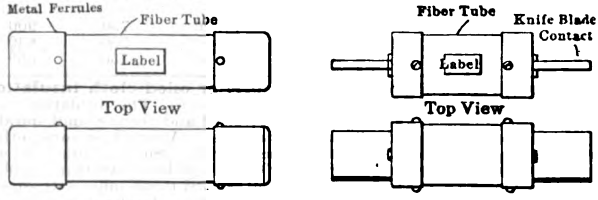


FIG. 10.—National Electrical Code standard enclosed fuses.

43. Three-way and four-way switches. Switches for controlling a group of lamps from either of two locations are wired as indicated in Fig. 7. Two "three-way" snap switches are required. This scheme is largely used in residences for the control of hall lamps. Switches for controlling a group of lamps from any one of more than two locations are connected as in Fig. 8. A "three-way" switch is used at each end of the circuit and as many additional "four-way" switches are necessary as there are additional control locations. This arrangement is used for hall lamps in residences and for "watchmen's" circuits in factories so that they can be controlled from any floor.

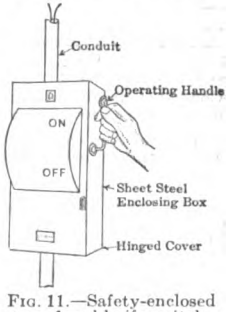


FIG. 11.—Safety-enclosed type fused knife switch.

44. Knife switches, except on panelboards and switchboards, should be of the safety-enclosed type (Fig. 11), wherein the switch is totally encased in a sheet-metal box which has an operating handle extending through its side. This is now a requirement of the *Chicago Electrical Code*. It will doubtless, in the future, find wide adoption, because of the decrease in life and fire hazard which it insures. An open knife switch, as experience has shown, is always a potential source of life and fire hazard.

45. Open-link fuses disrupt violently under conditions of short-circuit and blacken the panel that supports them. They are, if of specified construction, approved by the Code if supported on slate bases and enclosed in iron cabinets. When so arranged they render exceptionally good service in industrial plants if they are maintained by journeyman electricians.

46. Cartridge or enclosed fuses. The Code cartridge fuses (Fig. 10) are of two designs, the ferrule-contact type for currents below and in-

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cluding 60 amp. at 600 volts, and the knife-blade contact type for currents of from 61 to 600 amp. at 250 volts and of from 61 to 400 amp. at 600 volts. See *National Electrical Code* for detail dimensions of fuses of different capacities. A cartridge fuse usually consists of a tube of fiber or some similar material which enshrouds the fuse link. The link terminals are connected to contact pieces at the ends of the tube. An insulating powder surrounds the link and fills the tube. In some forms the fuse link is encased in a small air chamber, as illustrated in Fig. 12. The formation of destructive arcs is prevented in fuses of the cartridge type and the fuses themselves are capable of being very accurately rated.

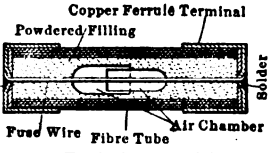


FIG. 12.—Typical enclosed-fuse construction.

47. The ratings of enclosed fuses are specified by the Underwriters' laboratories, in its publication "Standard For Cartridge Enclosed Fuses," thus:—"Fuses must be so constructed that with the surrounding atmosphere at a temperature of 24 deg. cent., they will carry indefinitely 110 per cent. current without causing the tubes to char or externally-visible soldered connections to melt. With a room temperature between 18 and 32 deg. cent., fuses starting cold must blow on 150 per cent. current without causing the tubes to char or externally-visible soldered connections to melt within the times specified in Par. **48.**

48. Time Intervals Within Which National-Electrical Code-Standard Enclosed Fuses Must Blow On 150 Per Cent. Rated Current

Rating of fuse, amperes	Maximum allowable time interval, minutes
0–30	1
31–60	2
61–100	4
101–200	6
201–400	12
401–600	15

49. Renewable fuses (Fig. 13) are those in which the fusible element, instead of the entire fuse, can be replaced by the user. They were not, until recently, approved by the Underwriters' laboratories. In spite of this they, because of their decided economic advantages, were widely used. The Underwriters' laboratories defines a standard cartridge-type renewable fuse thus:—"A fuse expressly intended by the manufacturer to be renewed by the user with suitable elements supplied by the manufacturer. Under this definition are included renewable fuses with separately enclosed renewable links, renewable fuses with renewal links not separately enclosed, and cartridge enclosed fuses with two or more links intended to be used successively." Renewable fuses are made in both the Ferrule-Contact and the Knife-Blade-Contact types and are approximately of the same over all dimensions as *Code* standard enclosed fuses. They fit the same cut-out as do standard enclosed fuses, are made in essentially the same capacities, and have about the same operating characteristics.

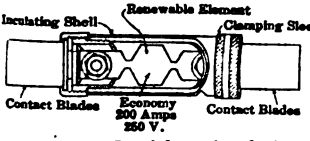


FIG. 13.—Partial sectional view of Economy knife-blade-contact-type renewable fuse.

50. Fusing currents of commercial fuse wire. The following values are approximate, as the fusing current is determined by the proportions and kinds of alloys used, kind and form of terminal, length of fuse and on other factors. (From Knox's "Electric Light Wiring;" table by Mr. Bathurst.)

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Nearest size A.W.G.	Diameter in inches	Fusing current in amperes
30	0.010	1.7
24	0.020	4.9
20	0.030	9.0
19	0.035	11.3
18	0.040	13.3
16	0.050	19.8
14	0.060	25.4
13	0.070	32.0
12	0.080	39.1
10	0.100	54.1
9	0.110	63.1
8	0.130	81.1
7	0.140	90.6
7	0.150	100.5
6	0.160	110.7
5	0.180	132.1
4	0.200	154.7

51. For a brief of code requirements relating to cut outs, see Par. 125. An automatic cut-out is a fuse or circuit breaker inserted in the circuit.

52. Diameters of Wires of Various Metals and Alloys that will be Fused by a Current of a Given Strength
(Knox's "Electric Light Wiring." Derived from tables of W. H. Preece)

Current in amp.	Copper		Aluminium		German silver		Iron	
	Diam. in in.	Nearest A.W.G.	Diam. in in.	Nearest A.W.G.	Diam. in in.	Nearest A.W.G.	Diam. in in.	Nearest A.W.G.
1	0.0021	43	0.0026	41	0.0033	39	0.0047	37
2	0.0034	39	0.0041	38	0.0053	35	0.0074	33
3	0.0044	37	0.0054	35	0.0069	33	0.0097	30
4	0.0053	35	0.0065	34	0.0084	31	0.0117	29
5	0.0062	34	0.0076	32	0.0097	30	0.0136	27
10	0.0098	30	0.0120	28	0.0154	26	0.0216	24
15	0.0129	28	0.0158	26	0.0202	24	0.0283	21
20	0.0156	26	0.0191	24	0.0245	22	0.0343	19
25	0.0181	25	0.0222	23	0.0284	21	0.0398	18
30	0.0205	24	0.2500	22	0.0320	20	0.0450	17
35	0.0227	23	0.0277	21	0.0356	19	0.0498	16
40	0.0248	22	0.0303	20	0.0388	18	0.0545	15
45	0.0268	21	0.0328	20	0.0420	18	0.0589	15
50	0.0288	21	0.0352	19	0.0450	17	0.0632	14
60	0.0325	20	0.0397	18	0.0509	16	0.0714	13
70	0.0360	19	0.0440	17	0.0564	15	0.0791	12
80	0.0394	18	0.0481	16	0.0616	14	0.0864	12
90	0.0426	18	0.0520	16	0.0667	14	0.0935	11
100	0.0457	17	0.0558	15	0.0715	13	0.1003	10
120	0.0516	16	0.0630	14	0.0808	12	0.1133	9
140	0.0572	15	0.0698	14	0.0895	11	0.1255	8
160	0.0625	14	0.0763	13	0.0978	10	0.1372	7
180	0.0676	14	0.0826	12	0.1058	10	0.1484	7
200	0.0725	13	0.0886	11	0.1135	9	0.1592	6
225	0.0784	12	0.0958	10	0.1228	8	0.1722	5
250	0.0841	12	0.1028	10	0.1317	8	0.1848	5
275	0.0897	11	0.1095	9	0.1404	7	0.1969	4
300	0.0950	11	0.1161	9	0.1487	7	0.2086	4

53. Cut-outs or fuse blocks are devices whereby fuses can be inserted in an electrical circuit. Detailed specifications covering cut-outs for all

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approved currents and voltages are given by the *Code*. A combination of the Edison plug cut-out, and the ferrule fuse and fuse-plug casing that can be used in connection with it, constitutes a most satisfactory fuse arrangement. However, this arrangement is limited to a capacity of 30 amp. at 125 volts. The Edison plug cut-out, which has a right-hand thread, is approved only for 125 volts; the Bryant Electric Co. makes a similar cut-out having a left-hand thread, which is approved, under certain conditions, for 250 volts. The right hand thread cut-out is approved for only 125 volts because the Edison fuse-plug, which is not safe at a greater voltage, can be used in it. Cut-outs for open-link fuses consist merely of slate blocks, having mounted on them the necessary terminals.

INTERIOR-WIRING-CIRCUIT CALCULATIONS

54. Interior-wiring-circuit terminology. To render definite the succeeding discussions, the following definitions are included. These specify the generally accepted meanings of the terms involved. See Fig. 14 for graphic definitions.

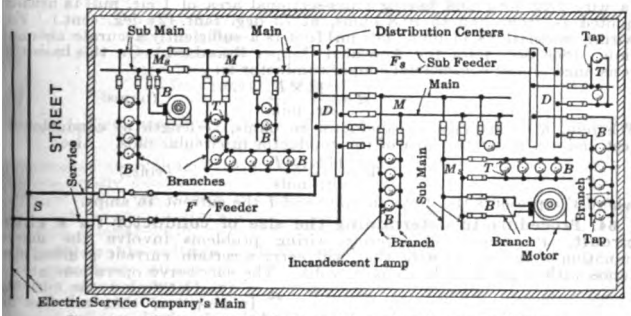


FIG. 14.—Illustrating interior-wiring-circuit nomenclature.

55. A feeder or feeder circuit (*F*, Fig. 14) is a set of conductors, in an interior-wiring system, extending from the original source of energy in the installation to a distributing center and having no other circuits connected to it between the source and the center.

56. A sub-feeder (F_s, Fig. 14) is an extension of a feeder, or of another sub-feeder, from one distribution center to another and having no other circuit connected to it between the two distribution centers.

57. A main (*M* Fig. 14) is any supply circuit to which other consuming circuits—sub-mains and branches—are connected through automatic cut-outs (fuses or circuit breakers) at different locations along its length. Where a main is supplied by a feeder, the main is frequently of smaller wire than the feeder which serves it. An energy-utilizing device is never connected directly to a main, a cut-out always being interposed between the device and the main.

58. A sub-main (M_s, Fig. 14) is a subsidiary main fed, through a cut-out, from a main, or from another sub-main, and to which branch circuits are connected through cut outs.

59. A service, or service connection (*S*, Fig. 14) is a set of conductors constituting an underground or overhead connection between a supply circuit (usually belonging to a public-service corporation) in a thoroughfare—street—and the interior or isolated wiring system. A "service" provides a path over which electrical energy is delivered to the consumers.

60. A branch or branch circuit (*B*, Fig. 14) is a set of conductors, feeding through an automatic cut-out (from a distribution center, main or sub-main) to which one or more energy-utilizing devices are connected directly, that is, without the interposition of additional cut-outs. The only cut-out asso-

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ciated with a branch is the one through which the branch is fed at the main sub-main or distribution center.

61. A tap or tap circuit (*T*, Fig. 14) is a circuit, serving a single energy-utilizing device, which is connected directly to a branch without the interposition of a cut out.

62. A distributing or distribution center (*D*, Fig. 14) in an interior-wiring system, is the location at which a feeder or sub-feeder main or sub-main connects to the subordinate circuits which it serves. The switches and automatic cut-outs for the control and protection of the sub-circuits are, usually, grouped at the distribution center. In interior-wiring parlance, a distribution center may be merely an arrangement or group of fittings whereby two or more minor circuits are connected at a common point to another larger circuit. A panel box is one form of distribution center.

WIRING CALCULATIONS AND LAYOUTS

63. The resistance of a circular-mil-foot of commercial copper wire (a wire 1 ft. long and having cross-sectional area of 1 cir. mil) is usually quoted as from 10.6 to 10.8 ohms, at 75 deg. fahr. (24 deg. cent.). For wiring calculations 11 ohms per mil foot is a sufficiently accurate assumption. (See Sec. 4 for the Annealed Copper Standard.) On this basis the resistance of any commercial copper conductor is:

$$R = \frac{11 \times l}{\text{cir. mils}} \quad \text{(ohms)} \qquad (1)$$

Wherein, R = resistance of conductor in ohms, l = length of conductor in feet and *cir. mils* = the area of the conductor in circular mils. Also:

$$V = \frac{11 \times l \times I}{\text{cir. mils}} \quad \text{(volts)} \qquad (2)$$

where V represents the drops in volts and I the current in amps.

64. Procedure in determining the size of conductor for a given circuit. Practically all interior wiring problems involve the determination of the size of wire that will carry a certain current a given distance with a permissible drop in volts. The successive operations are:

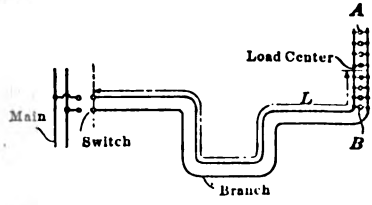


FIG. 15.—An example of load center.

(a) Determine the current, in amperes, that will flow in the circuit.

(b) Determine the distance from the point of assumed constant voltage to the load center of the circuit (Par. **65**). This distance will be the actual circuit length if the load is concentrated at one end.

(c) Decide what voltage drop or loss is allowable (Par. **66, 67** and **68**).

(d) Determine from the formulæ the size of wire that will give the desired voltage drop.

(e) Check the derived wire size for current-carrying capacity, using the table in Par. **27**.

(f) Where economy of operation must be considered, check the cost of the energy dissipated in resistance; this should be maintained within reasonable limits. See Par. **87** to and including **91**.

65. The load center of a circuit is that point at which it can be assumed that the total load is concentrated. The load center of a group of receivers, each of the same input and symmetrically arranged, will be at the middle of the group. (Fig. 15.)

To determine the load center of a group of receivers of unequal capacities or unsymmetrically located, first multiply the normal current taken by each receiver by its distance from the starting point of the circuit; add all the products thus found, and divide this sum by the total current of the circuit. See Fig. 16. After some experience, one can by inspection usually determine the location of the load center with sufficient accuracy. Calculations for this factor are seldom made by experienced circuit designers.

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66. Allowable voltage drop in incandescent lighting circuits, should not exceed 3 volts in 110-volt circuits and 6 volts in 220-volt circuits. Sometimes 4 or 5 volts drop is allowed in 110-volt circuits, but these are decidedly the upper limits and do not represent good practice. In percentages of the receiver voltage, a drop of from 1 to 3 per cent. is satisfactory and a 4.5 per cent. drop is the maximum. (See Par. **69.**) The above values represent the voltage drops from the source of assumed constant voltage to the lamp. Because of the extreme sensitiveness of the incandescent lamp to variations in voltage, the lamps may be subjected

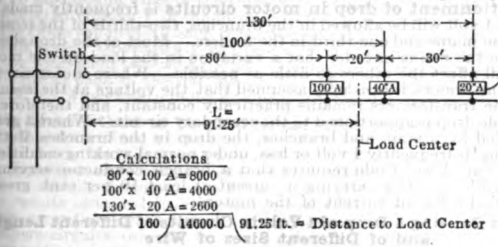


FIG. 16.—Determination of the load center of a circuit having receivers of unequal capacities, unsymmetrically located.

to excessive overvoltages if the drops suggested above are exceeded—which will materially decrease their life. They may also be subjected to undervoltages when the circuit is loaded—which will decrease their brilliancy (Sec. 14). Some central-station companies specify that the total drop in 110-volt, interior-wiring circuits shall not exceed 1 volt.

67. Allowable voltage drop in motor circuits. A 5 per cent. drop is in accordance with excellent practice and a 10 per cent. drop or even a slightly greater one is often considered satisfactory. These drops are reckoned on the receiver voltage. The drop should be calculated on the basis of full-load motor current. Where incandescent lamps are on the same circuits with motors the drops suggested in Par. **66** should not be exceeded. In designing motor circuits the question of conductor economy (Par. **88**) should be considered.

68. Typical Apportionment of Drop in 110-Volt Lighting Circuits

Part of circuit	Proportion	4 volts total drop		3 volts total drop	
		Actual drop, volts	Per cent. drop	Actual drop, volts	Per cent. drop
Branches	1 volt	1	0.91	1	0.91
Mains	¼ remainder	1	0.91	¾	0.60
Feeders	¾ remainder	2	1.82	1½	1.21
Total		4	3.64	3	2.72

69. Apportionment of voltage drop. In circuit design it is necessary to apportion the total drop among the various component circuits—feeders, mains, sub-mains and branches. In incandescent lighting most of the drop is confined to the feeders because if there were excessive drop in the mains and branches, lamps located close together but served by different mains and branches might operate at decidedly different brilliancies.

With an isolated plant, that is where energy is generated on the premises, the drop may be apportioned exactly as indicated (Par. **68**). Where the premises is served by a central station (Par. **70**), the practice of the utility concern may allow 2 volts drop in its secondary mains and the service to the premises. In such a case, the total drop within the premises should not exceed 1 to 2 volts. Where a utility company is to give service,

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it should be consulted regarding its practice in this respect. Some companies require that the voltage drop in interior wiring installations which they are to serve, shall not exceed a certain maximum. In any case, it is frequently the practice to allow one volt drop for the branches and to apportion the rest of the available drop to the main circuits and feeders.

70. Apportionment of drop on 2,400-volt distribution systems is often made under the assumption that the secondary voltage at the transformers remains practically constant. This will be found true in a well laid-out system, particularly if automatic feeder regulators are used.

71. Apportionment of drop in motor circuits is frequently made on the basis that 1 volt will be allowed in the branches, two-thirds of the remaining drop in the mains and one-third in the feeders. Most of the drop should be confined to the mains in order that a variation in the load on one motor of a group will affect the others as little as possible. Where motor circuits are fed by transformers, it is usually assumed that the voltage at the secondary side of the transformers remains practically constant, and therefore all of the allowable drop is apportioned to the secondary circuit. Where a group of motors is fed by a main and branches, the drop in the branches, if they are not too long, is frequently 1 volt or less, under normal working conditions, because the Nat. Elec. Code requires that a branch conductor serving a motor be capable of safely carrying a current at least 10 per cent. greater than the normal full-load current of the motor.

72. Currents Causing a Drop of 1 Volt in Circuits of Different Lengths and of Different Sizes of Wire

Size A.W.G.	Total length (*single distance*) of circuit in feet (The total length of wire is twice the single distance)								
	20 ft.	30 ft.	40 ft.	50 ft.	60 ft.	70 ft.	80 ft.	90 ft.	100 ft.
14	9.3	6.2	4.6	3.7	3.1	2.5	2.3	2.0	1.8
12	14.8	9.9	7.4	5.9	4.9	4.2	3.7	3.3	2.9
10	**23.6**	15.7	11.8	9.4	7.8	6.7	5.9	5.2	4.7
8	33.0	25.0	18.7	15.0	12.5	10.7	9.3	8.3	7.5
6	46.0	39.7	29.7	23.8	20.0	16.9	14.8	13.2	11.8
5	54.0	50.0	37.6	30.0	25.0	21.2	18.7	16.1	15.0
4	65.0	**63.2**	47.4	37.8	31.6	27.0	23.6	21.0	18.8
3	76.0	76.0	59.8	47.7	39.6	34.0	29.8	26.2	23.8
2	90.0	90.0	75.0	60.0	50.0	42.8	37.5	33.0	30.0
1	107.0	107.0	93.5	75.0	68.0	53.5	46.7	41.5	37.4
0	127.0	127.0	**119.8**	95.6	79.0	68.0	59.5	53.0	47.6
00	150.0	150.0	150.0	120.0	100.0	86.0	75.0	66.5	60.0
000	177.0	177.0	177.0	152.0	127.0	108.0	95.0	84.0	76.0
0,000	210.0	210.0	210.0	192.0	160.0	136.6	120.0	107.0	96.0
200,000 c.m.	200.0	200.0	200.0	**181.9**	151.5	129.9	113.6	101.0	90.9
300,000 c.m.	270.0	270.0	270.0	270.0	227.2	194.7	170.4	151.5	136.2
400,000 c.m.	330.0	330.0	330.0	330.0	303.0	259.7	227.2	202.0	181.8
500,000 c.m.	390.0	390.0	390.0	390.0	**378.8**	324.7	284.1	252.5	227.2
600,000 c.m.	450.0	450.0	450.0	450.0	450.0	389.5	340.8	303.0	272.7
700,000 c.m.	500.0	500.0	500.0	500.0	500.0	461.0	397.7	353.5	318.1
800,000 c.m.	550.0	550.0	550.0	550.0	550.0	519.5	454.4	404.0	363.6
900,000 c.m.	600.0	600.0	600.0	600.0	600.0	584.4	511.3	454.5	409.0
1,000,000 c.m.	650.0	650.0	650.0	650.0	650.0	650.0	568.7	505.0	454.5

Values below the heavy type exceed the maximum safe currents allowed by *The National Electrical Code* (Table 22) for rubber-covered wire.

73. Per cent. voltage drop in practical wiring calculations is usually taken as a percentage of the receiver voltage. The voltage drop may be expressed in percentage of impressed voltage by the expression $p = V/(E+V)$, where p is the per cent. drop, V is the drop in volts and E is the voltage at the receiver.

74. Calculation of two-wire, direct-current circuits is effected by means of the following formula,

$$\text{cir. mils} = \frac{22 \times I \times L}{V} \qquad (3)$$

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wherein V = drop in volts in the circuit, I = current in amperes, L = length one way or the single distance of the circuit, in feet and *cir. mils* = the cross-sectional area of the conductor in circular mils.

75. Calculations of three-wire, direct-current circuits are made with Eq. 3, Par. 74. In a balanced three-wire circuit no current flows in the neutral wire. In making wiring calculations in practice for three-wire circuits, it is assumed that the circuit is balanced. Ascertain the current that will flow in the outside wires of the three-wire circuit and then use Eq. 3, Par. 74. The drop in voltage V in the formula is the drop in both of the outside wires and is twice the drop to each receiver connected between the neutral and an outside wire. Obviously V can be twice as great for a three-wire circuit as for the equivalent two-wire circuit. The neutral wire if unfused should be the same size as each of the outside wires in order to conform with *Code* requirements, but when ungrounded and properly fused it may be smaller.

76. The method to be used in calculating an alternating-current circuit is determined by the characteristics of the circuit under consideration. Where the circuit is short and the conductors will lie reasonably close together, the approximate methods suggested in following paragraphs can be used; these partially disregard the effects of power-factor and line reactance. The results obtained from these approximate formulas are usually subject to less error than other factors entering into the ordinary wiring calculation. Where circuits are long and the conductors lie far apart, the results given by the approximate formulas should be checked by the Mershon-Diagram (Sec. 12) which considers the effects of power-factor and reactance. Although the Mershon method is a trifle tedious, it will usually be found the quickest and the best when all things are considered. The use of the tables, that are frequently given for the determination of alternating-current conductors, may lead to inaccurate results, unless the user is familiar with their derivation. The effects of capacitance (electrostatic capacity) are inconsequental and need not be considered in ordinary interior wiring calculations.

77. Line-reactance voltage drop may be decreased either by diminishing the distance between the wires, or by dividing the copper into a greater number of circuits. Reactance is little affected by changing the size of the conductor. In interior wiring installations the conductors can be no nearer together than certain minimum distances specified by the *National Electrical Code*. Where installed in conduit the conductors are so close together that their reactance is practically negligible. All the wires of any alternating-current circuit (two wires for a single-phase circuit, three wires for a three-phase circuit or four wires for a two-phase circuit) should be carried as close together as feasible or, in a conduit installation, they must all be in the same conduit, in accordance with the *Code*.

78. Skin effect in interior wiring calculations is ordinarily of little consequence, and need not be considered unless conductors are larger than 600,000 cir. mils in area. (Sec. 2 and Sec. 12.) As a general proposition conductors larger than 600,000 cir. mils are very difficult to handle, and, hence, are uneconomical to install; therefore, when greater area is required it is usual to arrange several conductors in parallel. Some engineers will use no conductor larger than 300,000 cir. mils in interior wiring. Fiber-cored cables (Par. **38** and **39**) should be used where conductors larger than 600,000 cir. mils are required.

79. Calculation of alternating-current circuits of high power-factor, such as those which supply incandescent lamps: in this case treat the circuits as if they were direct-current circuits, using Eq. 3, Par. 74. This method is not strictly accurate but is sufficiently so for ordinary conditions. If the circuits are long and the wires are widely separated, the conductor sizes obtained as above should be checked by the Mershon-diagram (Sec. 12).

80. To calculate single-phase, alternating-current circuits where line reactance may be neglected. The following formulas can be safely used for the calculation of branch circuits and also of feeders and mains where the conductors are carried in conduit or are not very long. Where the circuits are of considerable length the result given by the formula should

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be checked with the Mershon diagram (Sec. 12). The current may be found from the expression:

$$I_1 = \frac{Kw. \times 1{,}000}{E \times p.f.} \quad \text{(amps.)} \quad (4)$$

wherein, I_1 = current in amperes, $Kw.$ = kilowatts input of the load, E = voltage of circuit and $p.f.$ = power-factor of load.

$$\text{cir. mils} = \frac{22 \times I_1 \times L}{V}. \quad (5)$$

Wherein, *cir. mils* = area of conductor; I_1 = current in amperes; L = length (one way) of the circuit in feet and V = volts drop allowable.

81. **Calculations of single-phase branches from three-phase circuits** are made in the same way as those for any other single-phase circuit (Par. 80). However it must be remembered that if the branch is connected between one of the three phase wires and the neutral, the voltage impressed on the branch circuit will be 0.58 times the voltage across any two phase wires of the three-phase circuit.

82. **To calculate two-phase, four-wire, circuits where line reactance can be neglected** the following formulas can be used. The limitations for this method are the same as those for single-phase circuits as outlined Par. 80. As with the single-phase equations (Eq. 4 and 5, Par. 80), the Mershon diagram (Sec. 12) should be used for checking the conductors for circuits of considerable length. Where the current is not known it can be found thus:

$$I_2 = \frac{Kw. \times 1{,}000}{E \times p.f. \times 2} = \frac{Kw. \times 500}{E \times p.f.} \quad \text{(amps.)} \quad (6)$$

Wherein, I_2 = current in amperes in each of the four wires of a balanced two-phase circuit, and the other symbols have the same meanings as in Par. 80. The current being known:

$$\text{cir. mils} = \frac{22 \times I_2 \times L}{V} \quad (7)$$

Wherein all of the symbols have the same significance as outlined in this and preceding paragraphs. Use four wires of the same size.

83. **To calculate three-phase, three-wire, alternating-current circuits where line reactance can be neglected** the following formulas can be used. The limitations for this method are the same as those outlined for single-phase circuits in Par. 80. As with the single-phase equations the Mershon diagram (Sec. 12), should be used for checking the results obtained for circuits of considerable length. Where the current is not known, it may be obtained from the expression:

$$I_3 = \frac{Kw. \times 1{,}000}{E \times p.f. \times 1.73} = \frac{Kw. \times 580}{E \times p.f.} \quad \text{(amps.} \quad (8)$$

Wherein I_3 is the current in each of the three wires of a balanced three-phase, three-wire circuit, and where the other symbols have the same significance as in Par. 80. When the current is known, then

$$\text{cir. mils} = \frac{11 \times I_3 \times L \times 1.73}{V} = \frac{19 \times I_3 \times L}{V} \quad (9)$$

Wherein the notation is the same as outlined in this and preceding paragraphs.

84. **Calculation of single-phase circuits where line reactance must be considered.** The Mershon diagram (Sec. 12), is recommended for making such calculations. Other and apparently simpler methods are available, but all simple methods are inaccurate under certain conditions and are likely to get their user into trouble unless he is familiar with the derivation and limitations. The Mershon diagram does not offer a direct method of ascertaining drop; it is a "cut-and-try" method. Trials are made until a conductor size is found that will bring the drop within the specified limit. It is seldom that more than two trials are necessary. The method is a little tedious but not difficult, and will be found accurate under all ordinary conditions.

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85. To calculate a two-phase, four-wire, alternating-current circuit where line reactance must be considered, use the Mershon diagram (Sec. 12), calculating a single-phase circuit (Par. 80) which will transmit one-half the power at the same voltage. The two-phase transmission will require two such circuits.

86. To calculate a three-phase, three-wire, alternating-current circuit where line reactance must be considered, use the Mershon diagram (Sec. 12), calculating the conductor size for a single-phase circuit (Par. 80), which will carry one-half of the load at the same voltage. The three-phase transmission will require three such conductors.

87. Power loss in any circuit. Assuming that 11 ohms is the resistance of a circular-mil-foot of copper conductor, the power loss in any conductor may be found thus:

$$P = \frac{11 \times I^2 \times l}{\text{cir. mils}} \quad \text{(watts)} \qquad (10)$$

Wherein, P = power lost in the conductor in watts, I = the current in amperes in the conductor, l = length of the conductor in feet and *cir. mils* = area of the conductor in circular mils.

For a two-wire circuit (direct-current or single-phase).

$$P = \frac{2 \times 11 \times I^2 \times L}{\text{cir. mils}} = \frac{22 \times I^2 \times L}{\text{cir. mils}} \quad \text{(watts)} \qquad (11)$$

For a four-wire, two-phase circuit (assuming balanced currents)

$$P = \frac{4 \times 11 \times I^2 \times L}{\text{cir. mils}} = \frac{44 \times I^2 \times L}{\text{cir. mils}} \quad \text{(watts)} \qquad (12)$$

For a three-wire, three-phase circuit (assuming balanced currents)

$$P = \frac{3 \times 11 \times I^2 \times L}{\text{cir. mils}} = \frac{33 \times I^2 \times L}{\text{cir. mils}} \quad \text{(watts)} \qquad (13)$$

Wherein, P = the power, in watts, lost in the circuit; I = the current in amperes which flows in each of the wires of the circuit; L = the length (one way) of the circuit; and *cir. mils* = cross-sectional area in circular mils of each of the wires. The above formulas can be used only when all of the wires of the line are of the same size.

88. Conductor economy in interior wiring installations always should be considered as a matter which is subordinate to the Code requirements. Obviously any conductor selected for a specific installation must fulfil the requirements of mechanical strength, ample carrying capacity (Par. 24 and 27), and permissible voltage drop (Par. 66 and 67). Frequently one of these three considerations will definitely determine the size of the conductor; however, a calculation of the resistance or I^2R (power) loss (Par. 87) may indicate that it will be desirable to use a larger size than is otherwise necessary.

89. Annual charges may be considered, in connection with the economical selection of a conductor size, to be made up of two items: (*a*) *resistance-loss charges;* (*b*) *investment charges.* Resistance-loss charges depend upon the resistance, the current and the unit cost of energy, and may be decreased by an increase of conductor size. This, however, calls for a greater investment with consequently larger investment charges. A conductor should be selected of such a size that the total annual charge (Sec. 25) will be a minimum.

In Fig. 17 the effect of a variation of conductor size on resistance-loss charge, investment charge, and total annual charge is shown graphically. The interest charges on the conductor increase directly with its cross-sectional area (graph *A*, Fig. 17). The resistance-loss charges decrease inversely as the cross-sectional area of the conductor (graph *B*, Fig. 17). The total annual charge (graph *C*, Fig. 17), the sum of graph *A* and *B*, is at its minimum value directly over the point where graphs *A* and *B* intersect. That is, the conductor size that will have the least total annual cost is that one for which the annual interest charge equals the annual resistance-loss charge. This proposition (Par. 90) has been demonstrated mathematically by Lord Kelvin.

90. Kelvin's law was deduced in 1881 by Sir William Thompson (Lord Kelvin). The original law was modified into the following more exact form by Gisbert Kapp: "*The most economical area of conductor is that for which the annual cost of energy wasted is equal to the interest on that portion of the*

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capital outlay which can be considered proportional to the weight of copper used. On the basis of the above law it can be shown that:

$$\text{*cir. mils} = 55{,}867 \times I \times \sqrt{\frac{C_e}{C_c \times A}} \qquad (14)$$

Wherein: *cir. mils* = area in circular mils of the most economical conductor; I = the mean annual current (Par. **94**). C_e = cost of energy per kilowatt-hour, in dollars; C_c = cost of copper in dollars per pound, installed; A =

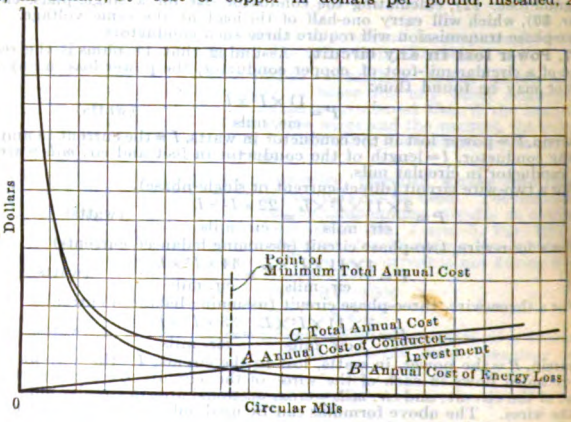


FIG. 17.—Graph illustrating Kelvin's law.

annual charge in per cent. on the cost of the conductor. This can ordinarily be assumed as about 10 per cent. Note that neither the length nor the voltage of the circuit are factors in the equation.

The method involving Eq. 14 is best adapted to cases where the conductors are not insulated. It should be used always in connection with the method of Par. **91**.

91. Another determination of conductor size may be followed in cases where the conductor cost will be large. This method is the preparation of a table showing energy costs and interest costs of an arbitrarily chosen length of conductor for a number of sizes.

Size rubber-covered conductor.....	No. 4 wire	250,000 c. m.	300,000 c. m.	400,000 c. m.	500,000 c. m.	600,000 c. m.
Cost of 400 ft. of conductor.....	$22.50	$102.40	$118.40	$150.40	$184.00	$218.20
Annual charges on above cost at 10%.	$2.25	$10.24	$11.84	$15.04	$18.40	$21.82
Cost of energy lost in conductor at 8 cents per kw-hr.....	$66.00	$10.56	$8.84	$6.60	$5.28	$4.49
Total annual cost of conductor.....	$68.25	$20.80	$20.68	$21.64	$23.68	$26.31

* For derivation see "The Electrical Engineer's Handbook," (International Textbook Company), page 311. See also "Transmission of Electrical Energy," by A. V. Abbott; "Electric Power Transmission," by Dr. Louis Bell; and "Overhead Electric Power Transmission," by Alfred E. Still.

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The cost of unit length of conductors (preferably 1,000 ft. or 305 m.) may be obtained from the manufacturers' wire lists. Power loss may be calculated from Eq. 10 to 13, Par. **87**.

By use of this table the situation may be made readily apparent, and a decision may be speedily reached. This method may be used as a check upon Eq. 14, Par. **90**.

92. In alternating-current systems of distribution there are the two-wire and three-wire single-phase systems; the three-wire and the four-wire, two-phase systems, and the three-wire and four-wire, three-phase systems. All of these are usually fed from the secondaries of transformers located outside the building, either on poles or in subways.

93. Single-phase, two-wire and three-wire systems of distribution are similar to the direct-current systems, and the same precautions should be taken in the three-wire system to balance the loads on each side of the neutral.

94. Factors for determining the mean annual current. To ascertain the mean annual current for substitution in Eq. 14, Par. **90**, multiply the maximum current by the ratio applying to the conditions under consideration, given in the column headed "*Factor*" in the following table. The table is calculated on a basis of 24 hr. × 365 days = 8,760 hr. per year.

Example. If a maximum current of 1,000 amp. (I) flows $\frac{1}{2}$ of the time or 6,570 hr. per year and a current of 750 amp. ($\frac{3}{4}I$) flows $\frac{1}{4}$ of the time or 2,190 hr. per year the factor "0.944" would be used; that is, the value 0.944 × 1,000 amp. = 944 amp. would be the mean annual current for substitution in the equation of Par. **90** (Eq. 14).

Proportion of time current is carried	Proportion of maximum current "I" carried				Factor
	$\frac{1}{4}I$	$\frac{1}{2}I$	$\frac{3}{4}I$	I	
	0	0	0	1	1.000
	0	0	$\frac{1}{4}$	$\frac{3}{4}$	.944
	0	$\frac{1}{4}$	0	$\frac{3}{4}$	.901
	0	0	$\frac{1}{3}$	$\frac{2}{3}$	.844
	0	0	0	$\frac{3}{4}$	.866
	$\frac{1}{4}$	0	0	$\frac{3}{4}$	.875
	0	$\frac{1}{4}$	$\frac{1}{4}$	$\frac{3}{4}$	.838
	0	0	$\frac{1}{3}$	$\frac{2}{3}$	.820
	$\frac{1}{4}$	0	$\frac{1}{4}$	$\frac{3}{4}$	.810
	0	$\frac{1}{3}$	0	$\frac{2}{3}$	.790
	0	$\frac{1}{4}$	$\frac{1}{3}$	$\frac{2}{3}$	.771
	$\frac{1}{4}$	$\frac{1}{4}$	0	$\frac{3}{4}$	.760
	$\frac{1}{4}$	0	$\frac{1}{3}$	$\frac{2}{3}$	.744
	$\frac{1}{3}$	0	0	$\frac{2}{3}$	.729
	0	$\frac{1}{3}$	$\frac{1}{4}$	$\frac{3}{4}$	.718
	0	0	0	$\frac{1}{2}$	.707
	$\frac{1}{4}$	$\frac{1}{4}$	$\frac{1}{4}$	$\frac{3}{4}$	.685
	0	$\frac{1}{4}$	0	$\frac{3}{4}$	.661
	$\frac{1}{4}$	0	$\frac{1}{4}$	$\frac{3}{4}$	.650
	$\frac{1}{2}$	$\frac{1}{3}$	0	$\frac{2}{3}$	.611
	$\frac{1}{4}$	$\frac{1}{4}$	0	$\frac{1}{2}$	.586
	$\frac{1}{2}$	0	0	$\frac{1}{2}$	.545
	0	0	0	$\frac{1}{2}$	.500

95. Two-phase distribution may be effected with four or with three wires. In the former case there is a pair of wires for each phase, while in the latter there is one wire for each phase and a common wire for both phases. The circuits must be balanced on either side, just as in the case of a three-wire, direct-current system, the only difference being that where three wires are used, the common wire is 1.4 times as large as either of

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the other two, since it must carry 1.4 times as much current. Motors are connected to both phases and employ all three or all four wires as the case may be. With four wires, the lamps are connected to each phase as though the supply were single-phase and care should be exercised to balance each phase as nearly as possible.

96. The three-phase system is usually employed where motors form a greater part of the load. Three conductors are necessary. Where lamps are required they are either balanced on the three-phases or connected between each main conductor and a common conductor of smaller size usually connected to the middle point of the star-connected secondary. The e.m.f. between any one of the three wires and the neutral is 0.577 (or 0.58) times the e.m.f. between the mains.

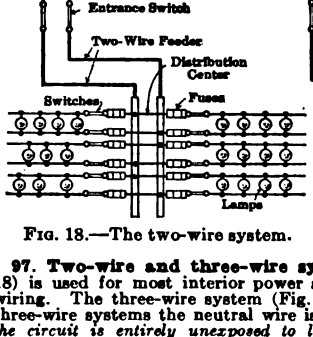


FIG. 18.—The two-wire system.

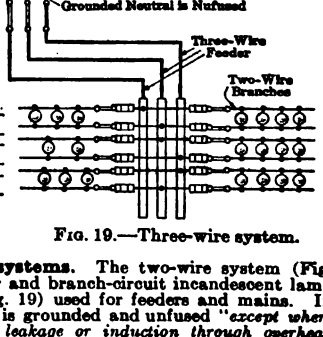


FIG. 19.—Three-wire system.

97. Two-wire and three-wire systems. The two-wire system (Fig. 18) is used for most interior power and branch-circuit incandescent lamp wiring. The three-wire system (Fig. 19) used for feeders and mains. In three-wire systems the neutral wire is grounded and unfused "*except where the circuit is entirely unexposed to leakage or induction through overhead construction from aerial circuits operating at pressures exceeding 600 volts.*" Hence the neutral is, except where there is no exposure to aerial circuits operating at pressures exceeding 600 volts, made the same size as each of the two outer wires. Hence the marked economy of copper which is theoretically possible with the three-wire system is not always realizable in interior installations. When the neutral is grounded the neutral wire must be the same size as the outer wires. See *Code* rules 15*a*, 15*b*, 23*b* and 15*Ab*.

When the neutral is grounded the three wires of the system are of the same size because if one of the outer fuses should blow, one side of the system would be loaded while the other side would carry no current. In such a case the neutral would have to carry the same current as the outer wire, and were it smaller than the outer wire it would be overloaded. Where a grounded neutral has the same cross-section as either of the outer wires, the neutral fuse is to be omitted; but not otherwise. By making the neutral of cross-section equal to the combined cross-sections of the outer wires, the system may be easily changed to a two-wire system. The latter plan is usually followed in large buildings, where a two-wire isolated plant is used and where the emergency connection with the utility company's mains is three-wire.

98. The load on a three-wire system must be balanced, that is, the watts load should be approximately the same on either leg of the three-wire circuit. A variation of 10 or 15 per cent. may be permissible. Good balance is particularly important at maximum load. Unbalance causes unequal voltages, which is noticeable as producing a non-uniformity of illumination, and it may bring an overload on the conductors.

99. Planning residence wiring. Secure the floor plans or inspect the building. Decide where the meter is to be located; the point of entrance should be as close to the meter as possible. A good arrangement is to locate the service entrance (Par. **107**) and the meter in the cellar. If the wires

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enter between the first and second floors, the meter may be installed in the rear hall. Ascertain how many lamp outlets there will be, their location, and the current required by each. Locate the distribution center at some central point convenient of access. Divide the incandescent-lamp outlets into groups which absorb less than 660 watts, each group being fed by one branch circuit from the distributing center. Not more than 16 standard-size sockets are permitted on branch circuit which serves incandescent lamps, except in special cases. See Par. **104**. It is best to subdivide the outlets so that no branch circuit will have an initial load greater than 440 watts, which allows 220 watts for growth, so that the maximum of 660 watts, specified by the *Code*, shall not be exceeded.

Locate the switches and calculate the feeders required. Incandescent lamp branch circuits are usually of No. 14 wire unless they are longer than 100 ft. (30.5 m), in which case wire at least as large as No. 12 should be used; No. 14 is the smallest size permitted by the *Code*. Fig. 19A shows a typical lay-out for a small residence. Usually one panel or a group of cut-outs is sufficient for a residence. It is always preferable to group all cut-outs instead of locating them at random. In a small building, branch cut-outs or the panel box can often be set near the meter at the entrance or in the hall. In a two-story house they can be installed in the cellar stairway or in the rear hall, and in a three-story building they can be installed in the second floor hall. Where there are more than three stories, distributing centers can be located every second or third floor.

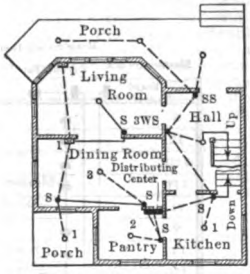


FIG. 19A.—Example of a conduit-wiring lay-out in a residence.

100. Important features of large lay-outs. There are five important factors that should be considered in designing the wiring lay-out for a large building (Knox, "Electric Light Wiring"). They are: (*a*) control of groups of receivers (other than hall or night lights) from the main switchboard; (*b*) control of hall lights from the main switchboard; (*c*) maximum load that should be served by one feeder; (*d*) the best maximum limit for the size of the feeder conductors; (*e*) the proportion of the total voltage drop that can be allowed in feeders and mains.

101. Wiring lay-out for a large building. Make a sectional-elevation drawing of the structure and a floor plan of each floor. Indicate the receivers (lamps and motors) on the plans and then so locate the panel boxes that no lighting branch circuit shall be much over 100 ft. (30.5 m) in length, or have a load much greater than 440 watts. Panel boxes should be so located that they are accessible and that the circuits can be readily run to them. Compute the load on each panel box and indicate it, at the box, on the drawing. Lay out the mains and feeders (see Fig. 20). First decide whether the hall or public lights will be controlled separately or with the private lights from the main switchboard, because this feature affects the arrangement of the feeders and possibly that of the mains. Next decide whether there should be a separate feeder to each floor or whether several floors or portions thereof will be served by one feeder. Where it is unnecessary to control the loads on the different floors separately, and where the resulting conductor size will not be prohibitively large, the cheapest and probably the best arrangement is to serve several or possibly all floors with one feeder. Usually, the only limit to the number of floors that may be served with one feeder is the refinement of control that is desired from the main switchboard. It is frequently necessary to make several tentative lay-outs and computations before the most desirable arrangement is found. Segregated motors and groups of motors, unless very small, should be served by independent feeders.

102. Arrangement of feeders. Solely on a basis of initial cost, it is usually cheaper to run a few large conductors than a number of small ones. It does not pay, however, to endeavor to install conductors larger than 1,000,000 cir. mils. When large capacity is necessary, use several conductors having the aggregate capacity required. For alternating currents, conductors

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larger than 700,000 cir. mils are not desirable because of skin effect. Often the space available for conductor runs necessitates small conductors (Par. **38** and **78**).

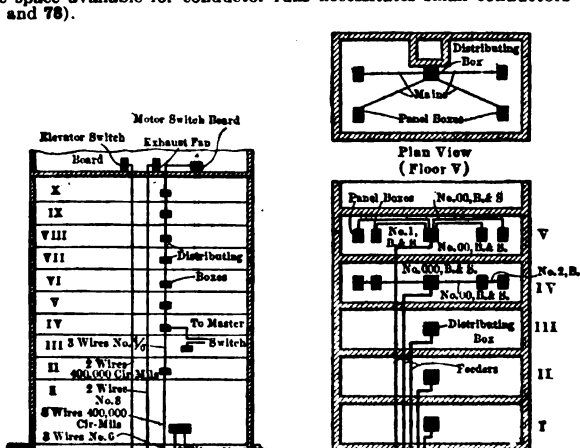


FIG. 20.—Wiring lay-outs in large buildings.

103. Motor circuits are subject to many special *Code* requirements. One unfamiliar with its rulings should consult the *Code* before he attempts to install motor wiring. The principal requirements follow: (*a*) Motor circuits must be designed to carry a current at least 10 per cent. in excess of that for which the motor is rated. (*b*) Where wires installed in accordance with this ruling would be overfused in order to provide for the starting current, the wires must be of such size as to be properly protected by these larger fuses. (*c*) Where alternating-current motor leads are rubber insulated, the wire may be protected in accordance with Table *C*, Par. **27**. (*d*) The rated capacity of the running fuses must not exceed 125 per cent. of the name-plate current rating of the motor, except where no standard size fuse exists, then the next higher standard fuse-size may be used. (*e*) To provide for the peak loads encountered in variable-speed motor service see ratings indicated in the *Code*. (*f*) Every motor installation (except for cranes) must be protected by a cut-out and must be controlled by a switch which plainly indicates whether it is on or off. (*g*) Small motors may be grouped under the protection of a single set of fuses, provided their aggregate capacity does not exceed 660 watts. (*h*) For motors of 0.25 h.p. or less on circuits at voltages of 300 or under, single-pole switches may be used. (*i*) Switch and starting box should be so located that they are visible from the motor.

Motor manufacturers always furnish with each machine a diagram of connections and instructions for installation. These data should always be consulted.

104. Electric heating-device circuits (see *National Electrical Code*). A heater of a capacity greater than 6 amp., or 660 watts should be protected by an individual cut-out and should be controlled by a switch or plug

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connector which indicates whether the device is "on" or "off;" this should be visible from the heater. Heaters of a capacity smaller than that indicated above can be grouped under the protection of a single set of fuses, *provided* the capacity of the fuse does not exceed 10 amp. Such heaters can also be connected individually to lighting circuits.

106. Heating device outlet plates will be found convenient; each is provided with a receptacle, a switch and an indicating lamp socket. They are regularly manufactured for current capacities as high as 20 amp. Keyless brass sockets have a maximum rating of 6 amp. Ordinary pull-chain and key sockets have a maximum rating of 2.5 amp. Standard separable attachment plugs are approved for 660 watts at 250 volts or 10 amp. at 110 volts. Where ordinary key sockets are used for switching heating devices, they soon break down under the action of the arcs due to the relatively heavy currents. Snap or knife switches should always be used for heating devices. Specially constructed asbestos-covered, flexible cords are required for all devices absorbing more than 250 watts. In a first-class installation, it is always desirable to install separate circuits for the heating devices, extending from the entrance switch to the receivers. This permits individual metering and insures that the heavy currents drawn by the heating appliances will not interfere materially with the voltage regulation of the interior lighting circuits.

CIRCUIT ANALYSIS

Location of Building _____ Date _____ 19?

Architect _____

Engineer _____

Owner _____

Estimate Transferred to General Analysis Sheet No. _____

Floor	Circuit	Outlets		Switches	Receptacles	Floor Receptacles	Feet of Pipe	Feet of Wire	Fittings		
		Side	Ceiling						Elbows	Couplings	Lock Nuts and Bushings
Total											

FIG. 21.—Sheet for estimating cost of wiring installations (actual size should be about 18 in. wide by 12 in. long).

106. Compilation of estimates. Experience and a reliable note-book of labor costs applying to the community under consideration are the most valuable aids. Read the specifications or inspect the premises and make a wiring lay-out if there is none available. Make a list (Fig. 21) of all material required, following some definite system. A good method is to consider each distribution center—one at a time—and tabulate all the material required for the circuits feeding from it. Number or letter the distribution centers in accordance with a certain scheme and designate the branches with subnotations. Indicate this notation on the estimating sheet similar to that of Fig. 21. Then proceed, tabulating panel-box, main, feeder and entrance material. After all is tabulated, the items can be totaled and these total values used for ordering material. Allow for some extra material for losses and breakages. Figure labor cost on a unit basis, that is, the cost of stringing wire being a certain value per 100 ft., the cost of erecting conduit being so much per unit length and so on through the entire list of materials. See cost data elsewhere for unit costs. A small job can be estimated with fair accuracy on a basis of so much per outlet, without the necessity of compiling a bill of materials.

INSTALLATIONS

107. Service entrances, (Fig. 22). A cut-out and a fuse block should protect the switch. The wall should be bushed with a non-combustible incubating tube where the conductors pass through unless they are in conduit, and the tubes or conduit should be cemented in the wall. Tubes should

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slant outwardly and downwardly to prevent the entrance of moisture. A drip loop should be formed in the service wires. The entrance switch should usually be so arranged that it will disconnect all of the equipment in the building. For permissible exceptions, see *Code* Rule 24. Where conduit is used, the two or the three rubber-insulated wires should be carried in one conduit.

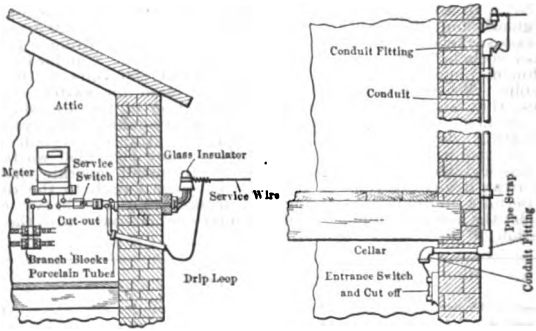


FIG. 22.—Service entrances.

108. Distribution center panels may consist merely of porcelain cut-outs held to the back of the box with wood screws, or may be more elaborate. The panel provides a convenient means of connecting the branch circuits to a main through fuses. Switches may be used in both main and branch circuits or they may be omitted entirely. Many satisfactory installations are in operation without switches at the distribution center but switches are a great convenience for opening circuits when replacing fuses or for testing. In general, knife switches should not be used for the control of the lamps, as they are frequently of improper design to withstand permanently such service. Individual lamp-group circuits should be controlled by either flush or surface snap switches mounted outside the panel box.

109. Standard wiring symbols adopted by the National Electrical Contractors' Association and the American Institute of Architects

(Copyrighted by the National Contractors' Association.)

(4) Ceiling outlet; electric only. Numeral in center indicates number of standard 16 c-p. incandescent lamps.

(4/2) Ceiling outlet; combination. 4 indicates 4–16 c-p. standard incandescent lamps and 2 gas burners. If gas only,

(2) Bracket outlet; electric only. Numeral in center indicates number of standard 16 c-p. incandescent lamps.

(4/2) Bracket outlet; combination. 4 indicates 4–16 c-p. standard incandescent lamps and 2 gas burners. If gas only,

(2) Wall or baseboard receptacle outlet. Numeral in center indicates number of standard 16 c-p. incandescent lamps.

(4) Floor outlet. Numeral in center indicates number of Standard 16 c-p. incandescent lamps.

(e) Outlet for outdoor standard or pedestal, electric only. Numeral indicates number of standard 16 c-p. incandescent lamps.

(6/6) Outlet for outdoor standard or pedestal; combination. 6 indicates 6–16 c-p. standard incandescent lamps; 6 gas burners.

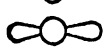
FIG. 23A.

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Drop cord outlet.


One-lamp outlet, for lamp receptacle.


Arc lamp outlet.


Ceiling fan outlet.


Special outlet for lighting, heating and power-current, as described in specifications.


S. P. switch outlet.


D. P. switch outlets.


3-way switch outlet.


4-way switch outlet.


Automatic door switch outlet.


Electrolier switch outlet.

Show as many symbols as there are switches. Or in case of a very large group of switches, indicate number of switches by a roman numeral, thus; S' XII; meaning 12 single pole switches.

Describe type of switch in specifications, that is, flush or surface, push button or snap.


Meter outlet.


Distribution panel.

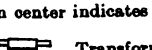

Junction or pull box.

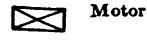

Motor outlet. Numeral in center indicates horse power.

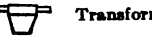

Motor control outlet.

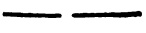

Transformer.


Main or feeder run concealed under floor.


Main or feeder run concealed under floor above.


Main or feeder run exposed.


Branch circuit run concealed under floor.


Branch circuit run concealed under floor above.


Branch circuit run exposed.


Pole line.

Riser.

Telephone outlet; private service.


Telephone outlet; public service.


Bell outlet.

Buzzer outlet.


Push button outlet. Numeral indicates number of pushes.

Annunciator. Numeral indicates number of points.


Speaking tube.


Watchman clock outlet.


Watchman station outlet.


Master time clock outlet.


Secondary time clock outlet.


Door opener.


Special outlet for signal systems, as described in specifications.


Battery outlet.


Circuit for clock, telephone, bell or other service, run under floor, concealed. Kind of service wanted ascertained by symbol to which line connects.

Circuit for clock, telephone, bell or other service, run under floor above, concealed. Kind of service wanted ascertained by symbol to which line connects.

HEIGHTS OF CENTER OF WALL OUTLETS (unless otherwise specified):

Living rooms	5 ft. 6 in.
Chambers	5 ft. 0 in.
Offices	6 ft. 0 in.
Corridors	3 ft. 6 in.
Height of switches (unless otherwise specified)	4 ft. 0 in.

FIG. 23B.

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110. Installation of watt-hour meters and maximum-demand meters. (*Rules and Regulations of the Commonwealth Edison Co., Chicago*): Meter loops should be provided in the mains at an accessible location, and so arranged that the meter may be mounted with ordinary wood screws on the wall. A meter board must be provided of sufficient size to allow the installation of a watt-hour meter and maximum-demand meters. Two maximum-demand meters are installed on three-wire mains. Maximum-demand meters will not be installed on installations under 1 kw. Sufficient space must be provided about the meters to allow the removal of the case.

Meter boards should not be erected on a wall which is subject to any considerable vibration, or in places subject to excessive moisture or heat. A pressure-wire tap must be provided in all cases where all wires of the circuit are not looped out. On three-wire mains the pressure-wire tap must be made on the neutral wire. The general arrangements of meter loops should be such that a meter can be installed without crossing any wires, if possible. If this is impracticable, sufficient flexible tubing should be left on the wires to make possible an installation which will be in accordance with the wiring rules.

Meter loops should not be placed above 7 ft. from the floor, and should be as near the point of entrance of the service as possible. In office buildings meter loops should be located at a central point in meter closets or public corridors, and in apartment buildings in the basement of the building, so that meters may be installed and maintained without annoyance to tenants.

Meter loops must be located relative to fuses so that meters are protected by the fuses. They must never be placed between the service and the service switch. Generally speaking, not more than one meter installation will be provided for the same class of service in any one building.

Meter loops for service supplying temporary lighting or power to new buildings during construction must be located on adjoining premises. No three-wire meters larger than 200 amp. are used. Installations requiring meters of larger capacity will be provided with two meters, one on each side of the three-wire main; space should be allowed accordingly in arranging meter boards.

111. Protection of watt-hour meters against unauthorized or malicious interference is effected by means of seals and enclosing cabinets. See manufacturers' catalogues for further information, and "Metermen's Handbook," published by the National Electric Light Association.

112. Panel boxes are cabinets arranged to contain distribution-center panels or cut-outs and switches for protecting and controlling branch circuits where they are tapped from a main. It is desirable, in so far as possible, to group cut-outs in a wiring system; to this is due the popularity of panel boxes. Originally boxes were made without gutters; their disadvantage was that it was necessary to carry the entering wires for each branch circuit to a point opposite their proper cut-out. When the boxes are provided with suitably-proportioned gutters (*Code* Rule 26, o) (now the usual form), conductors can enter the gutter at the most convenient point and can be carried in the gutter to a point opposite the cut-out. This arrangement results in material savings, particularly in conduit work.

Panel boxes may be either of the surface type, which extends wholly beyond the wall, or of the flush type, which does not extend beyond the wall. Surface-type boxes are used principally for factory wiring and for conduit installations in old buildings.

Panel boxes of sheet steel are suitable for factory work. The barriers in boxes with wooden gutters, are usually of slate or marble. The inside of a wooden box must be completely lined with a non-combustible insulating material. Slate or marble 0.25 in. (0.64 cm.), thick, or asbestos board 0.125 in. (0.32 cm.) thick may be used. Where iron conduit enters a box, the lining may be of either 0.25 in. (0.64 cm.) slate or marble, of 0.125 in. (0.32 cm.) asbestos board or of 0.062 in. (0.16 cm.) galvanized or painted sheet steel. Boxes should be painted inside and out. An asbestos or steel lining is preferable because slate or marble breaks easily. The door should close against a rabbet in order to be dust tight. Glass panels, 0.125 in. (0.32 cm.) thick, may be used in the doors. A 2-in. (5.08 cm.) space should be provided between the fuses and the door.

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113. Cost of interior wiring. Prices of labor and material differ in various localities and at different times. It is, therefore, difficult to state even approximately what the cost of interior-wiring systems should be. In large cities, these variations are not extreme and it is possible to state the limits within which the cost, expressed in terms of the usual contractor's price per outlet, should lie. The approximate figures given below apply to interior wiring of all classes, from the small residence to the large hotel or office building. They cover the portion of the work from the main source of supply, assumed to be at the building line. In case the building is lighted from its own plant, these figures will apply to the portion of the installation lying between the lamp and the plant switchboard. No lamps, fixtures or reflectors are included in these prices:

Exposed wiring, $3.00 to $5.00 per outlet. The data are based on large-city material and labor conditions for the year 1919, the pay rate of a journeyman wireman being $8.00 per 8-hour day. For other conditions the costs should be modified accordingly.

Wire in metal raceway, $5.00 to $7.00 per outlet.

Concealed knob and tube wiring, $3.50 to $4.00 per outlet, with $1.00 added per switch outlet.

Wiring in iron conduit and in new buildings, $8.00 to $11.00 per outlet.

Wiring in iron conduits in concrete buildings, $9.00 to $12.00 per outlet.

In the above, switches and base-board plugs are considered as outlets when the iron box is included. If the switch and plate are also to be furnished, approximately $1.00 per outlet of this nature should be added. For the larger installations in modern buildings the price of $9.00 per outlet, including all wiring and feeders up to the lighting fixture, has been found to be a fairly close figure.

114. Estimating costs of conduit installations. The Treasury Department of the United States uses the following method for computing the material required for conduit wiring in federal buildings. (Nelson S. Thompson, *Electrical World*, Sept. 9, 1911.) The material is taken off accurately from the drawings. The total amounts of conduit and wire are the lengths scaled from the plan plus the following: *Number of ceiling outlets* $\times 2$ *ft.; number of bracket outlets* $\times 10$ *ft.; number of switch outlets* $\times 10$ *ft.; number of baseboard outlets* $\times 4$ *ft.; number of two-gang switches* $\times 15$ *ft.;* and *number of three-gang switches* $\times 20$ *ft.*

115. Cost per foot for installing flexible steel-armored conductor (Bx) (Fig. 6) is, for the No. 14-wire size: 10 cents per foot for labor and 10 cents per foot for material making a total cost of 20 cents per foot installed complete.

116. Cost of pulling wire into conduit. The figures are based on the same labor and material conditions as those outlined in Par. **122.**

A. W. G.	Cost: Dollars per foot			A. W. G. or circular mils	Cost: Dollars per foot		
	1 wire	2 wires	3 wires		1 wire	2 wires	3 wires
14 Duplex	.....	$0.01	.....	0	$0.06	$0.038	$0.030
14	.....	0.006	$0.005	00	0.07	0.045	0.035
12	.....	0.008	0.007	000	0.08	0.050	0.040
10	.....	0.010	0.009	0000	0.10	0.060	0.045
8	.....	0.014	0.010	300,000	0.11	0.070	0.060
6	.....	0.016	0.014	400,000	0.13	0.085	0.080
4	.....	0.020	0.018	500,000	0.15	0.100	0.10
3	.....	0.025	0.020	600,000	0.18	0.120	0.11
2	.....	0.030	0.023	700,000	0.20	0.130	0.13
1	.....	0.035	0.025	800,000	0.21	0.150	0.15
.....	.....	.....	.....	900,000	0.22	0.160	0.16
.....	.....	.....	.....	1,000,000	0.25	0.180	0.18

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117. Labor cost for roughing in outlets. The figures are based on same labor and material conditions as those outlined in Par. **122**.

Fitting	Non-fireproof construction		Fire-proof construction	
	A	*B*	*A*	*B*
Ceiling outlet	$0.20	$0.30	$0.35	
Bracket, switch or base-plug outlet	0.25	0.40	0.40	
T fixture hanger	0.55	0.80	0.65	$0.90
⅜-in. fixture stud	0.03	0.04	0.05	0.10
Floor box	1.75	2.00	2.00	3.00

118. Cost of channelling for conduit, per foot: brick, $0.25; green concrete, $0.30; set concrete, $0.40. These figures are based on conditions as outlined in Par. **122**.

119. Cost of installing expansion bolts, each, in: soft brick, $0.13; green concrete, $0.18; set concrete, $0.25. These figures are based on conditions outlined in Par. **122**.

120. Cost of installing distribution cabinets (labor cost only) including: (1) *setting box*, (2) *mounting panel*, (3) *placing trim*, (4) *connecting up* and (5) *testing out*, is approximately $0.75 per circuit. This figure is based on conditions specified in Par. **122**.

121. Miscellaneous finishing labor-costs. These costs cover; (1) *placing;* (2) *making connections;* (3) *soldering (if necessary);* (4) *putting on plate;* (5) *testing*. The figures below are based on conditions specified in Par. **122**.

Item	Cost, dollars	Item	Cost, dollars
Single-pole switch	0.25	Ground wire, for lighting, No. 4	1.50
Double-pole switch	0.40	Ground wire, for motor, No. 10	0.70
Three and four-way switch	1.50	Ground wire, for motor, No. 4	1.20
Door-operated switch	2.00	30-amp., 2-wire meter loop	1.10
Base plug receptacle	0.25	30-amp., 3-wire meter loop	1.40
Drop cord	0.50	60-amp., 3-wire meter loop	2.75
1-light factory fixture	0.75	100-amp., 3 wire meter loop	6.00
Lighting panel per circuit	0.35	Signal bell	0.50
Ground wire, for lighting, No. 10	1.20	Push buttons	0.50

122. Cost per foot of installing conduit (roughing in). The following values show costs of conduit installed but without wire. See following table for cost of pulling in wire. Labor costs based on pay rate of $8.00 per 8-hour day for journeymen wiremen and $4.00 per day for helpers. Conduit material costs are averages for the year 1919. Add extra labor for cutting openings, channelling and other special work. Class "*A*" construction is open conduit work and simple concealed work. Class "*B*" construction is open conduit work in fireproof buildings and difficult concealed work. All costs are given in dollars.

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Size conduit	Cost of conduit per foot	Labor cost installing conduit, per foot		Total cost conduit installed		Cost of elbows, each	Labor cost installing elbows		Total cost elbows installed	
		A	*B*	*A*	*B*		*A*	*B*	*A*	*B*
½	0.085	0.06	0.10	0.145	0.185	.....	All 1 and 3 in. elbows are bent in conduit and are included in labor cost of installing conduit.			
¾	0.115	0.08	0.11	0.195	0.225	.....				
1	0.170	0.10	0.12	0.270	0.290	0.37	0.18	0.23	0.55	0.60
1½	0.230	0.12	0.14	0.350	0.370	0.45	0.25	0.30	0.70	0.75
1½	0.275	0.16	0.18	0.435	0.455	0.60	0.50	0.60	1.10	1.20
2	0.370	0.21	0.21	0.580	0.580	1.10	0.75	0.75	1.85	1.85
2½	0.585	0.27	0.27	0.855	0.855	1.80	1.00	1.00	2.80	2.80
3	0.765	0.32	0.32	1.085	1.085	4.80	1.25	1.25	6.05	6.05
3½	0.920	0.45	0.45	1.370	1.370	10.60	1.75	1.75	12.35	12.35
4	1.090	0.55	0.55	1.640	1.640	12.25	2.25	2.25	14.50	14.50

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123. Percentage increases of certain wiring materials since 1914–1916. This table was compiled in January 1920, (see *Electrical Review*, Jan. 3, 1920).

Material	Per cent. increase
Batteries, dry	75
Cabinets and cut out boxes	80
Conduit, interior	100 to 150
Fiber	50
Fittings, conduit	80 to 200
Fuses	25
Panelboards	80
Receptacles, flush	50 to 70
Sockets	50 to 75
Switches, knife	50
Switches, snap	50 to 100
Wire: Lamp cord	100
Wire: Rubber-covered	55 to 85
Wire: Weatherproof	100

124. A typical estimating sheet which illustrates the method used in practical interior-wiring estimating is reproduced in Fig. 24. Labor and material costs are computed on a unit basis. Sheets much more elaborate than that illustrated are in use but for the average condition it will satisfy every requirement.

PROTECTION

125. General principles regarding the use of fuses. Fuses or some other form of overload protection should be used where the protection of conductors or appliances against overload is desirable. The *National Electrical Code* specifies (Rule 23) in detail as to their application. Constant-potential generators should be protected against overload by fuses or their equivalent. Single-pole protection is acceptable under certain conditions for direct-current generators. Fuses should be placed at every point where a change is made in the size of wire, unless the fuse on the larger wire is of such capacity that it will protect the smaller one.

Fuses must be inserted in all ungrounded service wires, and must be located in an accessible place as near the entrance to the building as possible.

In grounded-neutral three-wire systems, the neutral wire is not fused. No group of small receivers, whether motors, incandescent lamps or heating appliances, requiring more than 660 watts should in general depend on one cut-out. For theatre wiring, outline lighting, signs and large fixtures 1320 watts may be dependent on one cut-out; *Code* Rule 23d. The rated capacity of a fuse protecting any wire should not exceed the safe carrying capacity of that wire as specified in Par. **27**. Each wire for a motor circuit, except at a switchboard, should be protected by a fuse whether or not circuit-breakers are used, except where the motor is of such large capacity that fuse protection cannot be obtained, in which case it is only possible to use circuit-breakers.

126. Fuses vs. circuit-breaker. Fuses possess a time element of operation (see Fig. 25) which circuit-breakers do not have unless specially designed therefor. Due to this property, fuses delay the opening of an over-loaded circuit, where the operation would be practically instantaneous with circuit-breakers; fuses, then, may be preferable for motor circuits and for circuits that are subject to very brief overloads, especially where expert supervision of electrical apparatus is maintained, as in large mills and factories. Where there are many fuse replacements, the cost of fuse renewals is considerable.

Circuit-breakers can be reset in less time and with less trouble than is required to replace blown fuses, and no spare parts are required. Circuit-breakers may, therefore, be preferable where the time saved by their use is an important consideration. The first cost of the circuit-breaker equipment is much more than the cost of fuse equipment, but under severe service the circuit-breakers will prove less expensive in the end.

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ESTIMATE SHEET

SUBJECT *New Electric Lighting Installation, Building No.16*

OWNER *Mississippi Textiles Company* DATE *Jan. 20-1920*

LOCATION *Jefferson & Grand Aves.* BUILDING *Building No.16*

BID TO *M.T.Co.* ARCHITECT *John Smith Company*

CONTRACTOR

QUANTITIES ESTIMATED	MATERIAL	LABOR	MATERIAL	QUANTITIES ESTIMATED	MATERIAL	LABOR	MATERIAL
1104	Boxes-Outlet	386 40	110 40		BROUGHT FORWARD	2335 85	2597 97
62	" Switch	24 80	9 20		Cutouts		
32	" Receptacle	12 80	9 60		Fuses (Renewable)		535 00
2	" Junction	3 00	15 00		Panel Boards (300 Circuits)	225 00	2780 00
1000	Bolts and Studs	50 00	20 00		Panel Boxes		
2300	Bushings		31 91		Service Boards		
58	Reflectors	8 70	43 50	32	Receptacles	8 00	24 00
64	Sockets	9 60	16 00		Switches - Snap		
64	Canopies and Receptacles	12 80	25 60		" Knife		
4600	Lock Nuts		28 68	62	" Flush	15 50	22 68
26	40-Watt Lamps		7 80		Screws, Solder, Tape, Etc.		50 00
38	75-Watt Lamps		22 80	52,000	14 Wire	312 00	549 04
9000	½ Conduit	600 00	584 30	1050	12 "	8 40	14 49
2160	⅜ "	172 80	165 25		10 "		
6040	1 "	404 00	459 43		8 "		
660	1¼ "	79 20	100 95	360	6 "	5 04	18 71
120	1½ "	19 20	22 06	840	4 "	15 12	61 32
300	2 "	189 00	222 75	240	2 "	5 52	25 44
400	2½ "	108 00	156 48	255	1 "	6 38	35 37
700	3 "	224 00	358 17	825	" 1/0	25 05	139 19
25	3½ "	11 25	16 06	3150	" 2/0	131 25	761 25
	4 "			150	" 3/0	6 00	37 16
	1 Elbows			990	" 300,000	59 40	364 22
6	1¼ "	1 50	2 43	157	" 4/0 (leaded)	15 70	66 48
3	1½ "	1 50	1 62		Freight		
50	2 "	37 50	43 58		Cartage		50 00
10	2½ "	10 00	14 20		R. R. Fare		
8	3 "	10 00	30 42		Board		
	Ground Clamps				Expenses		
	Hangers				Inspection		85 00
	Moulding-Metal				Labor	3474 21	3175 00
	" Fittings				Drafting		
6	Red Globes		9 00		TOTAL		11392 22
130'	3-Way Vitrified Clay Duct	39 00	18 72		INCIDENTALS 2½%		284 81
130'	Concrete (162½ cu ft.)		52 00				11677 03
					OVERHEAD 15%		1751 55
					PROFIT		
	AMOUNT FORWARD	2335 85	2597 97		BID $ TOTAL		$ 13428 58

FIG. 24.—A typical estimating sheet.

127. Grounding the neutral of three-wire circuits. It is important that the ath through the neutral remain intact. rounding promotes this condition, and e *Code* requires it under most conditions explained in Par. **97.** See *Code* rules 5*Ab*, 15*Ad*. Normally in a well-designed stem, the neutral carries a minimum rrent. Frequently, in underground sys-ms, a bare copper wire drawn in the ucts constitutes the neutral. If the utral becomes open, the pressure nor-ally existing between the outer wires ay be imposed on the equipment con-ected between the neutral and an outer ire. Under these conditions the equip-ent may be ruined and a fire may result,

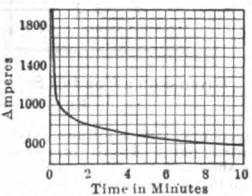


FIG. 25.—Typical performance curve of a 400-ampere, 500-volt, National Electrical Code standard fuse.

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since the voltage thus imposed will be twice that for which the equipment was designed.

128. Alternating-current, low-voltage, secondary circuits must be grounded. This is the recommendation of the *Code* rule 15*b* and is the practice of progressive central-station companies. Grounding minimizes accidents to persons and damage, by fire, to property. If some point of a low-voltage secondary circuit is grounded, no point of the circuit can rise above its normal potential (except under unusual conditions) in case of a breakdown between primary and secondary windings of the transformer, or of other accidental connection between the primary and secondary circuits. See the *Code* for further information regarding grounding.

The ground connection should be made at a neutral point or wire if one is

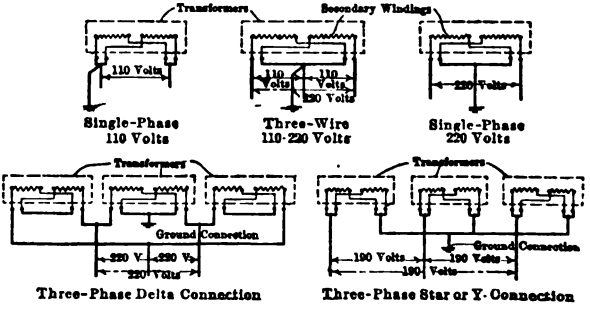
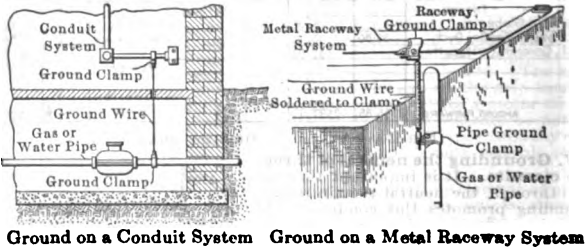


FIG. 26.—Ground connections to secondaries of commercial transformers.

accessible. Where no neutral point is accessible, one side of the secondary circuit may be grounded (*Code* rule 15*b*). Fig. 26 illustrates how some of these connections are arranged with commercial transformers. The neutral point of each transformer feeding a two-phase, four-wire secondary, should be grounded, unless the motors taking energy from the secondary have



Ground on a Conduit System Ground on a Metal Raceway System

FIG. 27.—Methods of grounding.

interconnected windings. Where they are interconnected, the center or neutral point of only one transformer is grounded. No primary windings are shown in the illustration and the secondary winding of each transformer is shown divided into two sections, as in commercial transformers.

129. All metal conduit and metal raceway systems must be grounded (see Fig. 27), by attaching an approved clamp (there are many on the market) to a conduit or raceway of the system and connecting it with a ground wire to another clamp attached to a water pipe on the street

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side of the meter. The wire must be soldered in the clamps. All parts of the conduit or raceway system must be in good electrical contact. In an ungrounded system of conduit, "sneak" currents are possible. These leak from one wire to the conduit through an abrasion of insulation and reach the other side of the line through another ground. The resistance of the path may be sufficient to hold the "sneak" currents below the line fuse capacity, and yet these currents may be sufficient to start a fire. Grounding the conduit also eliminates the possibility of electrical shock to persons coming in contact with the conduit. In combination fixtures the gas pipe should be in thorough electrical contact with the conduit or raceway system at each outlet box.

Wire for grounding ordinary conduit or raceway runs must be of copper or of other metal which will not corrode excessively (*Code* Rule 15*Aj*) at least No. 10 A. W. G. gage, where the largest wire contained in system is not greater than No. 0 A. W. G. gage; it need not be greater than No. 4 A. W. G. gage where the largest wire contained in conduit is greater than No. 0 A. W. G. gage. Service-conduit ground wires shall be not less than No. 8 gage copper. All ground wires must be protected from mechanical injury.

MISCELLANEOUS

130. Wire for bell signal work in dry places is usually No. 18 copper, double-cotton-covered and paraffined. Where more than two or three bells or similar devices are connected to the circuit, or where the circuits are long, No. 16 wire should be used. No. 14 is frequently used for battery wires. Rubber-covered, twisted-pair wires, like those employed for interior telephone wiring, can often be used to advantage in damp places or where the circuits are exposed. No. 20 wire, although sometimes used, is too small for reliable work. Annunciator and twisted-pair wire is made with insulating coverings of different colors, so one can be selected that will match the surroundings, and be inconspicuous. Cables of annunciator wire, which can be obtained with practically any number of conductors from 2 up to 200, are very convenient and economical for large installations. In perfectly dry locations, a cable having a paraffined, braided-cotton covering can be used, but if it is to be exposed to dampness a lead-covered cable should be installed. By having the cable conductors covered with braids of different colors, the conductors can be readily identified. A kind of weather-proof wire called "damp-proof," is quite satisfactory for exposed wiring in damp places. It is more expensive than annunciator wire, but it has a better appearance when installed. See the *National Electrical Code*, the "Telephone" section in this book and the Western Electric Co. catalogue for further information.

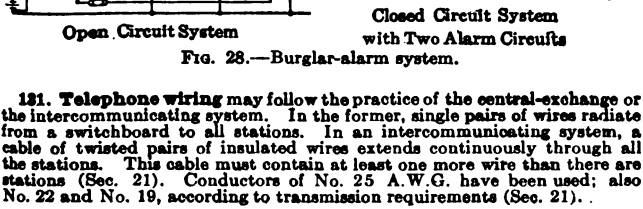


FIG. 28.—Burglar-alarm system.

131. Telephone wiring may follow the practice of the central-exchange or the intercommunicating system. In the former, single pairs of wires radiate from a switchboard to all stations. In an intercommunicating system, a cable of twisted pairs of insulated wires extends continuously through all the stations. This cable must contain at least one more wire than there are stations (Sec. 21). Conductors of No. 25 A.W.G. have been used; also No. 22 and No. 19, according to transmission requirements (Sec. 21).

132. Fire alarm wiring should be very carefully and substantially installed. As a general proposition, the wires should be heavier than would be used in ordinary signal practice; nothing smaller than No. 14 should be used indoors and nothing smaller than No. 8 out of doors. For interior lines, rubber

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insulated copper should be used, while for outside construction, weather-proof copper wire is satisfactory. The simplest possible arrangement consists of an alarm gong connected to a battery and a group of single-pole switches that are normally open. In case of fire one of the switches is closed and the alarm rings until it is stopped.

Burglar-alarm systems (see Fig. 28) may be divided into two general

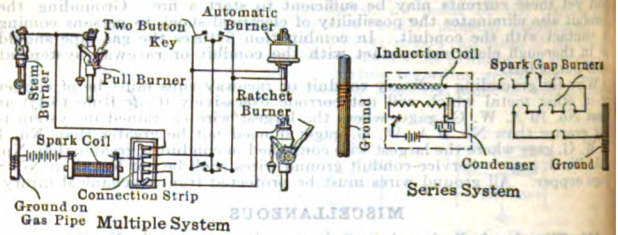


FIG. 29.—Electric gas-lighting circuits.

classes: (1) *The open-circuit system*, in which the circuits for the protected doors and windows are normally open, and when a circuit is closed by the opening of a door or window, an alarm is sounded. (2) *The closed-circuit system* in which the alarm is sounded by the opening of a circuit normally closed. Open-circuit systems are simpler, but closed-circuit systems are more

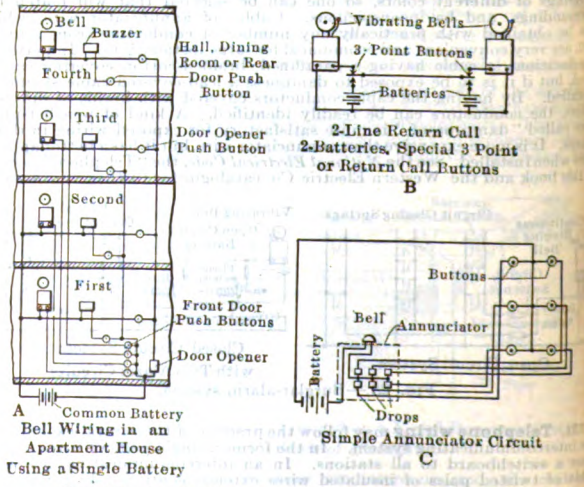


FIG. 30.—Typical electric bell and annunciator circuits.

sensitive and provide better protection; in the latter if the circuit is opened at *any point*, the alarm is sounded. Annunciators and burglar alarm fittings to be used in connection with either system are obtainable for the protection of doors, windows, shades, transoms and locks. See the "American Electricians' Handbook."

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133. Electric gas-lighting wiring (Fig. 29) may follow the multiple system or the series system. In the multiple system a spark is made by the breaking of an electrical circuit containing a reactance coil. One side of the circuit is usually grounded on the gas pipe. Electrically equipped burners of many types are obtainable. Certain spark coils are equipped with relays which sound an alarm if the system becomes short-circuited. Open circuit cells are used, a battery of 6 Leclanché cells in combination with a spark coil being usually sufficient.

In the series system, a spark gap is installed at each burner. The spark may be fed from induction coils or from frictional or static machines. The series system may be best adapted to large auditoriums, where many lamps are used in groups. It is now seldom used because such places are almost invariably lighted with electricity. See the "American Electricians' Handbook."

134. Electric bell and annunciator wiring. The possibilities for different circuit combinations are almost numberless. Those shown in Fig. 30 are typical. Two ordinary vibrating bells will not work well together in series; so when it is necessary to connect two bells in series, one should be a single-stroke bell. A multiple arrangement is preferable. The best arrangement of battery cells may be determined by trial. An ordinary bell requires about 0.1 amp. for its operation. Return call-bell circuits (*B*, Fig. 30) are so arranged that, when a station is signalled, the party called can respond by pressing his button. Ground return circuits may be used but are undesirable. Continuous-ringing bells are so arranged that, when the button is pressed, the bell continues to ring until reset. For elevator annunciators a cable is used, having as many conductors as there are buttons and one additional battery wire. If two annunciators are to operate simultaneously, their drops should be connected in series. See the "American Electricians' Handbook" for further information.

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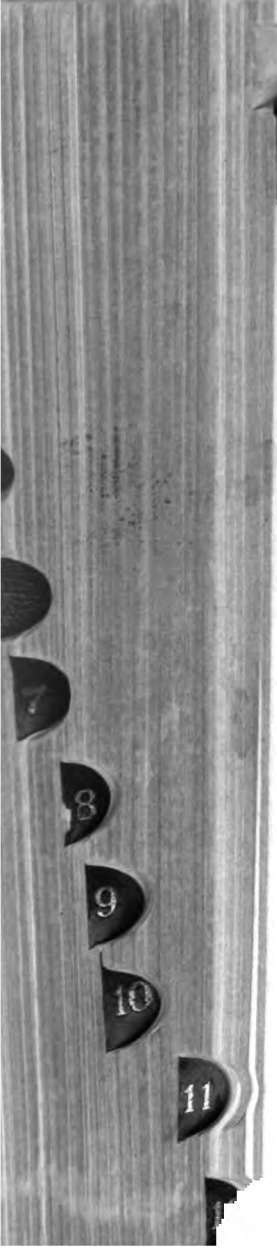
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SECTION 14

ILLUMINATION

BY PRESTON S. MILLAR

General Manager, Electrical Testing Laboratories; Past-President, Illuminating Engineering Society; Member, American Institute of Electrical Engineers, etc.

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SECTION 14

ILLUMINATION

PRODUCTION OF LIGHT

GENERAL THEORY OF LIGHT PRODUCTION

1. Light may be defined as radiant energy of those wave lengths to which the human eye is sensitive. Energy, of a nature with which the problem of light production is concerned, is radiated through a number of octaves forming the spectrum. The human eye is stimulated to vision only by that radiation which is between wave lengths 0.76μ and 0.38μ, or one octave. ($\mu = 0.001$ mm.) The limits of visibility are not definitely fixed, but those given are reasonably typical.

2. Incandescence is that process of light production, classed as temperature radiation, in which a body, usually a solid or a liquid, produces light without altering its nature in the process. The spectrum of such radiation usually is continuous.

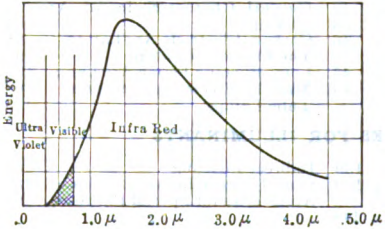


FIG. 1.—Radiation from "black body."

3. Pure temperature radiation is not completely realized in ordinary light sources, but it characterizes the theoretical **"black body"** which radiates the maximum possible energy at all wave lengths (Fig. 1). According to the **Stefan-Boltzmann law**, the total radiation of such a body is proportional to the fourth power of its absolute temperature

$$R = a\,(t+273)^4 \qquad (1)$$

t is the temperature in deg. cent. a is a measurable constant.

4. Wein's displacement law* shows that the relation between the wave length of maximum radiation intensity and the absolute temperature is a constant, which, for a black body has been determined to be 2940.

$$\lambda_{max} = \frac{2940}{T} \qquad (2)$$

λ in microns. (micron is 0.001 mm.)

Wein has shown further that the intensity at wave length of maximum black-body radiation varies as the fifth power of the absolute temperature. The intensity of radiation at any wave length is obtained from the **Planck formula** as follows:

$$J = \frac{C_1}{\lambda^5\left(e^{\frac{C_2}{\lambda\theta}} - 1\right)} \qquad (3)$$

* For exposition of derivation of equations and discussion of subject, see Drysdale, "The Production and Utilization of Light." *The Illuminating Engineer*, London, 1909, p. 230 and Bulletin, Bureau of Standards, Vol. VII, p. 395.

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where

J = radiation intensity; C = constants;
θ = temperature in deg. abs. and e = logarithmic base

Curves of radiation from a black body, computed according to this law, appear in Fig. 2.

5. Perfect black-body or temperature radiation is not found in artificial illuminants. Among incandescent electric lamps it is approached—most closely by "untreated" carbon-filament lamps (10-watt, 110-volt and 50-watt, 220-volt types)—in lesser degrees by "treated"-carbon, "metallised"-carbon and tungsten-filament lamps. The carbon filaments depart from a black body less than does platinum, for which a displacement-law constant (Par. 4) of 2630 has been found.

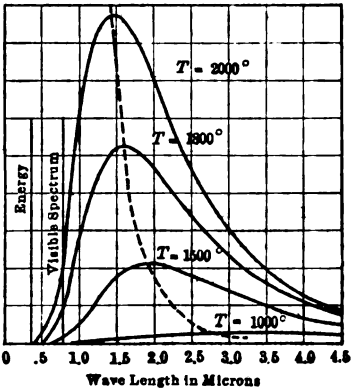


FIG. 2.—Black-body radiation at several temperatures.

6. Gray-body radiation is distributed throughout the spectrum in the same proportions as black-body radiation, but is everywhere less intense. It differs from black-body radiation in quantity, not in quality.

7. Selective radiation is distributed differently throughout the spectrum and does not obey the laws of black-body radiation. If it is relatively strong between the limiting wave lengths of visibility, particularly if near the middle of the visibility range, the body produces more light, and the selectivity is favorable. Curves of black-body, gray-body and of one kind of selective radiation are given in Fig. 3.

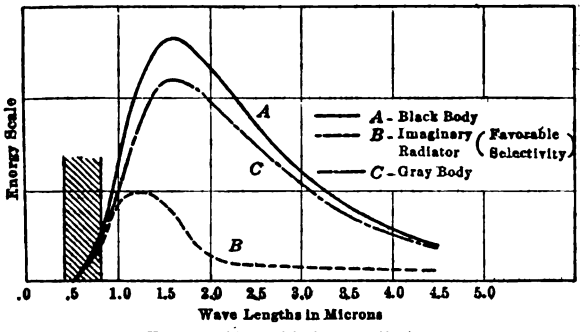


FIG. 3.—Three kinds of radiation.

8. Luminescence is that form of light production in which the radiating body (usually a gas or vapor) changes its nature in the process. Such radiation usually is characterized by a line spectrum. Luminescence embraces all forms of light production other than incandescence. In electric lighting it is the process by which light is obtained from gases or vapors. The mercury-vapor and the metallic-electrode (magnetite a

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metallic-flame) arc-lamps are examples of this method of light production. Radiation by luminescence may be strongly localised in a few lines of the spectrum, as in the mercury-vapor lamp (Fig. 4), or may be distributed so generally as to approximate, for many illuminating purposes, a continuous spectrum. It usually manifests more pronounced selectivity than is found among incandescent solids. Unlike temperature radiation, luminescence is characterized by fixed spectral distribution of radiation, this being independent of the intensity of the excitation.* .

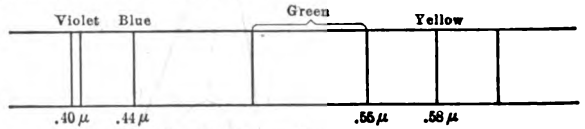


FIG. 4.—Visible spectrum of mercury arc.

9. Luminous efficiency. The problem of light production is in part that of radiating as much as possible of the energy within limits of visibility represented by wave lengths of 0.76μ to 0.38μ. There are two expressions for the efficiency with which this is accomplished. These are "**total luminous efficiency**" (radiation efficiency) or the ratio of energy radiated within the visibility range, to that expended in the illuminant; and "**radiant luminous efficiency,**" or the ratio of energy in the visibility range to the total radiated energy.† For an incandescent electric lamp in which most of the applied energy is converted into radiant energy, the two luminous efficiencies do not differ widely. For a multiple arc lamp in which a material part of the energy is not applied at the arc, the difference is large. Both total and radiant luminous efficiencies are of interest chiefly to the physicist, neither affording a real measure of illuminating efficiency. Both deal exclusively with the total energy radiated between visibility limits, ignoring the distribution of such energy. As a given energy radiated at 0.55μ will produce say ten times as great an illuminating effect as if radiated at 0.65μ or 0.45μ, consideration of the distribution of radiation is essential from the illuminating standpoint.

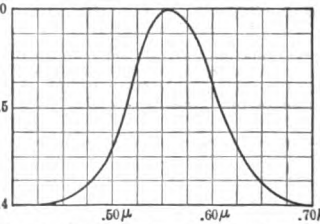


FIG. 5.—Visibility curve for human eye.

10. Visibility. Ratio of luminous to radiant flux for various wave lengths is plotted in Fig. 5, maximum visibility being taken as unity.‡

11. The illuminating power of radiation of any wave length is proportional to the product of the energy and the coefficient of eye sensibility. The problem of efficient light production is largely that of radiating as much as possible of the energy at wave lengths to which the eye is most sensitive. This may be taken as 0.55μ although the wave length of maximum sensibility varies with the intensity (Fig. 5), being shifted toward the shorter wave lengths as the intensity of the stimulus is reduced. Radiation would have the highest possible light value if it were concentrated at or near 0.55μ.

12. The "mechanical equivalent of light" is the ratio of radiated energy within given wave-length limits, to the illuminating power of such energy. It may be expressed in watts-per-candle or watts-per-lumen. There can be no one value for the mechanical equivalent of light applicable to all illuminants, if all energy in the visible range is included, because of

* Nichols and Merritt. *Physical Review*, Vol. XIX. p. 18.
† "Luminous Efficiency," *Transactions* Illuminating Engineering Society, Vol. V, p. 113.
‡ *Trans.* I. E. S., 1918, p. 523.

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the variation of eye sensibility with wave length. If, however, a narrow band of spectral radiation be separated and studied, a definite and reproducible ratio between energy and light value may be obtained. And if this band be selected from the part of the spectrum where the light value is highest (say 0.55μ), the minimum possible mechanical equivalent of light will result. Ives,* having compared with his own the experimental data and calculations of other investigators, has assigned the value of 0.02 watt per mean spherical candle, or 0.0016 watt per lumen, as the most probable mechanical equivalent of yellow-green light, to which the eye is most sensitive.

With this criterion of light producing efficiency available for the highest point of the ocular-luminosity curve (Fig. 5), a scale of ordinates for that curve is established, and the curve yields the sensibility coefficient for each wave length. This applied to the radiation curve (Fig. 2), gives a curve of visibility, from which the total illuminating power may be integrated. The value so obtained should equal the candle-power or the lumens as measured by a photometer. The value of mean spherical candle-power per watt or of total lumens per watt, when stated in terms of the most efficient light per watt, yields the "reduced luminous efficiency." (Drysdale's terminology.) The table of Par. 13 shows data of this kind based upon Ives' compilation.

13. Efficiency of light production

(Electrical World—Vol. LVII, p. 1566)

	Watts per mean sph. c-p.	Per watt		Reduced luminous efficiencies (based on radiated energy)
		Mean sph. c-p.	Lumens	
				Per cent.
Yellow-green 0.55μ	0.02	65	800	100
Firefly	.....	.....	.....	96
Black-body, about 5,000 deg. abs.	.....	10	125	15
Ditto, excluding energy outside limits 0.76μ to 0.38μ.	.....	22	274	34
Ditto, excluding energy outside limits 0.70μ to 0.40μ.	.....	26	330	41

14. In "reduced luminous efficiency" (see Par. 12) we have a very practical measure of efficiency of light production, because for any illuminant the ordinary commercial rating is directly comparable with the standards of highest possible efficiency. With this system of rating, everything depends upon the correctness of the standard of light production. But it may be noted that all artificial illuminants are so low in efficiency that a considerable error in fixing the standard would not alter materially the conclusions as to the inefficiency of illuminants. Standards for this purpose appear in Par. 16.

15. White-light efficiency. "Reduced luminous efficiency" (Par. 14) is the light flux per watt in per cent. of the yellow-green flux obtained from 1 watt radiated at 0.55μ. Such yellow-green light would be undesirable for most illuminating purposes. The generally accepted ideal is white light. Ives† has proposed the radiation between 0.70μ and 0.40μ from a black body at 5,000 deg. abs. as a standard of white light, and has assigned 330 lumens per watt as the most probable value of the most efficient white light obtainable. This is a satisfactory criterion for illuminating purposes. Ives‡ also has studied the spectrophotometric curves of some of the common incandescent sources to ascertain what proportion of their light is available to

* Luminous Efficiency, *Trans.* I. E. S., Vol. V, p. 113; Hyde, Forsythe and Cady, *Phys. Rev.*, Vol. XIII, p. 45.

† *Electrical World*, Vol. LVII, 1909, p. 1566.

‡ Bulletin, Bureau of Standards, Vol. VI, p. 238.

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form white light. Assuming colored absorbing screens of exactly the desired values to transmit with minimum loss that part of the radiation of each wave length necessary to produce white light, he has shown the "white-light" or "daylight efficiency" of each source. These values appear in Par. 17.

16. Light-producing efficiencies of certain electric illuminants

Light source	Mean spherical c-p. per watt	Lumens per watt	Reduced luminous efficiency
			Per cent.
Radiation at 0.55μ	65	800	100
Radiation from black body at 5,000 deg. abs.—excluding that outside 0.7μ and 0.4μ.	26	330	41
Mazda vacuum lamp—1.0 w.p.c.	0.78	9.8	1.2
Mazda gas-filled lamp—1000 watts.	1.53	19.3	2.4
Magnetite-arc—4.0 amp	0.85	10.7	1.3
Flame-arc—10-amp.—white-light carbon—approximate.	1.4	17.6	2.2

17. White-light efficiencies of incandescent lamps

Lamp	Watts per mean spherical c-p.	Lumens per watt	White-light efficiency	White-light lumens per watt	Per cent. of most efficient white-light (330 lumens per watt)
			Per cent.		Per cent.
Carbon	4.85	2.59	7.6	0.195	0.06
Carbon	3.75	3.35	8.6	0.29	0.09
Gem	3.10	4.05	10.0	0.405	0.12
Tantalum	2.60	4.83	10.0	0.485	0.15
Tungsten	1.56	8.05	13.7	1.10	0.33

18. Physical and physiological aspects of white light. Both the standard of white-light efficiency and the values shown for common illuminants are values for continuous-spectrum light from incandescent sources. That is to say, this method provides only for true white light, which is satisfactory physically as well as physiologically. Light produced by luminescence, which has a line spectrum, may be accepted as white in a physiological sense, but may fail to serve for certain illuminating purposes where true white light is required. It is doubtful if such light should be compared with true white light upon the same terms. At any rate notation should always be made of the peculiarities of spectral distribution of such light.

CHARACTERISTICS OF ELECTRIC LAMPS

INCANDESCENT LAMPS

19. Incandescent electric or glow lamps produce light by process of incandescent or temperature radiation. Hyde* has estimated that if operated at the same true temperature, the several filaments, due to **favorable selectivity,** would be more efficient than untreated carbon, which is least selective. Relatively these efficiencies are as follows: untreated carbon, 100 per cent.; tantalum, 110 to 112 per cent.; tungsten, 125 to 130 per cent.

20. The resistance characteristics of the more common types are shown in Fig. 6,† where 100 per cent. corresponds with the standard rated efficiency

* Lectures on Illuminating Engineering, I. E. S.—Johns Hopkins University.
† Lewinson. "Modern Incandescent Lamps"—School of Mines Quarterly, Vol. XXXIII, April, 1912.

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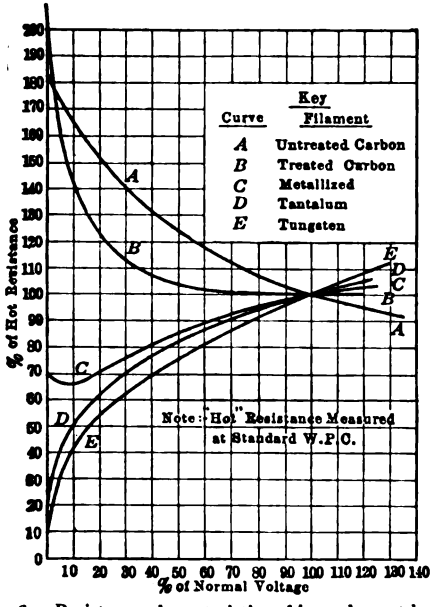


FIG. 6.—Resistance characteristics of incandescent lamps.

21. Resistance of filament lamps

Lamp	Cold resistance	Resistance at standard efficiency
watt untreated-filament	1062 ohms	582 ohms
watt treated-carbon	459 ohms	225 ohms
watt metallized-carbon	156 ohms	222 ohms
watt tantalum	44 ohms	262 ohms
watt tungsten	16.5 ohms	206 ohms

22. The physical characteristics of these lamps (Par. **20**) are shown in g. 7, 100 per cent. volts corresponding with rated efficiency. Throughout range of a few volts above and below normal, these relations may be ex-ssed as parabolic equations.

$$\frac{W_1}{W_2} = \left(\frac{e_1}{e_2}\right)^k \qquad (4)$$

The exponents* are not determined beyond question. Best known values e given in Par. **23**, and are reasonably accurate throughout a working nge of voltage variation. Par. **24** shows corresponding exponents for the riation in life with change in watts per candle.

* Edwards, E. J. *General Electric Review*, March, 1914.
Middlekauff and Skogland. Bureau of Standards Scientific Paper, No. 8.
Lewinson. *Trans.* I. E. S., 1916, p. 815.

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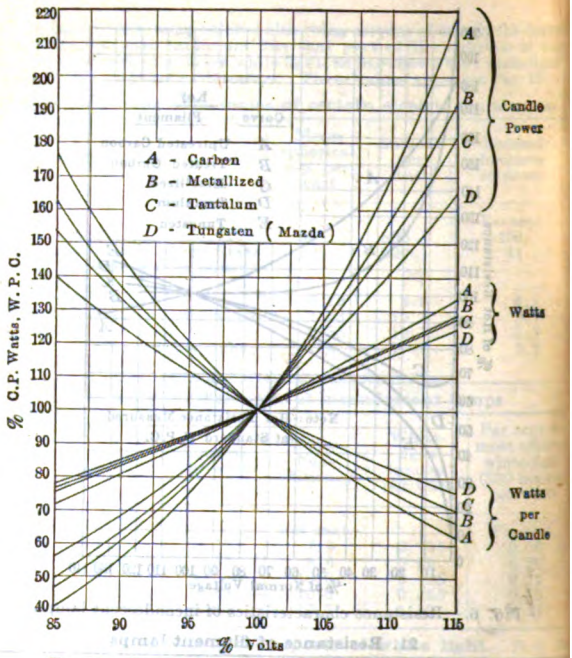


FIG. 7.—Characteristic curves of incandescent lamps.

23. Exponents (k) (Par. 22)

	Untreated carbon	Treated carbon	Metallized carbon	Tantalum	Tungsten
Candle-power	6.89	5.55	4.72	4.35	3.61
Watts	2.31	2.07	1.77	1.74	1.58
Watts-per-candle	−4.59	−3.48	−2.95	−2.61	−2.03
Amperes	1.31	1.07	0.77	0.74	0.58
Life	−25.2	−20.3	−17.2	−16.2	*

* −11.2 to −14.8 varying in general with size of lamp.

24. Watts-per-candle—life exponents

Type	Exponent (approx.)	Type	Exponent (approx.)
Tungsten	5.6 to 7.4	Treated carbon	5.82
Tantalum	6.23	Untreated carbon	5.49
Metallized carbon	5.86		

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25. Ives compilations of spectrophotometric and colorimetric values of illuminants

Source	Energy value by wave-lengths										Sensation values		
	0.41μ	0.43μ	0.47μ	0.49μ	0.53μ	0.55μ	0.57μ	0.59μ	0.65μ	0.69μ	Red	Green	Blue
1 Black body at 5,000 deg. abs.	72.0	79.0	91.0	92.5	98.0	99.0	100.0	100.0	97.1	93.5	33.3	33.3	33.3
2 Blue sky S	177.0	185.0	180.0	162.0	132.0	120.0	108.0	100.0	82.0	72.5	26.8	27.2	46.0
C											32.0	32.2	35.8
3 Overcast sky											34.6	33.9	31.5
4 Afternoon sun											37.7	37.3	25.0
5 Hefner	1.9	3.5	10.5	16.3	37.5	53.2	74.5	100.0	210.0	320.0	50.5	40.3	6.2
											55.0	38.8	6.2
6 3.1-w.p.c. carbon lamp	4.0	7.0	18.0	25.5	47.0	62.0	79.0	100.0	176.0	234.0	50.9	40.6	8.5
											51.3	40.4	8.3
7 Acetylene	5.5	9.6	21.9	30.3	52.0	66.5	82.0	100.0	160.0	205.0	48.1	41.0	10.9
											49.1	40.5	10.5
8 Tungsten 1.25 w.p.c	6.5	10.2	22.8	31.5	52.5	66.5	82.0	100.0	158.0	201.0	47.9	41.1	11.0
											48.7	40.5	10.9
9 Nernst											49.2	40.7	11.1
10 Welsbach, ¼ per cent. cerium											42.5	40.8	16.7
11 Welsbach, ½ per cent. cerium			26.4	38.3	64.0	78.0	90.0	100.0	114.0	120.0	45.2	42.0	12.8
											45.5	42.0	12.5
12 Welsbach, 1¼ per cent. cerium											47.2	41.8	11.0
13 D. C. carbon arc		21.8	37.0	45.5	65.5	76.0	88.0	100.0	142.0	170.0	41.0	36.3	22.7
14 Mercury arc											29.0	30.3	40.7
15 Yellow flame arc											52.0	37.5	10.5
16 Moore carbon dioxide tube											31.3	31.0	37.7

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26. Commercial ratings
(February, 1920)

Filament	Initial rated values: Watts	Mean horizontal c-p	Total lumens	Commercial rating-watts per mean horizontal c-p.	Specific consumption: Watts per mean spherical c-p.	Specific output: Lumens per watt
100 to 130 volts						
Carbon—untreated.....	10	2.0	21.2	5.0	5.88	2.12
Carbon—treated.....	50	16.8	174.5	2.97	3.61	3.49
Tungsten (Mazda).....	40	37.7	370.0	1.06	1.36	9.24
Tungsten—gas-filled.....	200	.....	310.0	.....	0.81	15.51

27. The color values of these lamps are shown through spectrophotometric values in Par. **25.*** White light (black body at 5,000 deg. abs.) is taken as standard. As compared with white light, all these incandescent lamps depart so largely that the differences among the several lamps seem relatively small. As a matter of fact, differences, for example, between the color of light from a Mazda lamp and that from a carbon lamp are far from negligible.

28. The flicker of lamps upon alternating current is important, when operation upon the lower frequencies is considered. Flicker phenomena are so complicated by a number of physical and physiological factors, that no unqualified definite statement can be made as to the lowest frequency upon which lamps may be operated without causing undue annoyance. The variables which enter into the problem are chiefly the following:

Physical	Physiological
Flicker is less for positive resistance temperature coefficient (as tungsten) than for negative coefficient (as carbon).	Flicker is less noticeable when illumination intensity is low.
Flicker is less for thick filament of given substance than for a thin filament.	Eye is most sensitive to flicker when light enters at about 45 deg. from centre of field of view, and falls upon peripheral portions of retina.

Stroboscopic data, showing extreme variation in candle-power through a half cycle, are presented in Fig. 8.† These show the gradual decrease in

* Ives. "Color Measurements of Illuminants," *Trans*, Illg. Eng. Soc., Vol. V, 1910, p. 208.

† C. H. Sharp. *Transactions* American Institute Electrical Engineers, 1906, p. 815.

Allowable Amplitude and Frequency of Voltage Fluctuations in Incandescent Lamp Work, by Herbert E. Ives, Illuminating Engineering Society *Transactions*, 1909, Vol. IV, p. 709.

The Frequencies of Flicker at which Variations of Illumination Vanish, by Kennelly and Whiting, National Electric Light Association *Transactions*, 1907, Vol. I, p. 327.

"Tungsten Lamp," by G. S. Merrill, *Transactions* of the American Institute of Electrical Engineers, 1910, Vol. XIX, p. 1907.

"Metal Filament Lamps," by John W. Howell, *Transactions* of the American Institute of Electrical Engineers, 1910, Vol. XIX, Part II, p. 927.

"Relative Advantages of 25 and 60 Cycles," by Philip Torchio and W. C. L. Eglin, *Transactions* of the Association of Edison Illuminating Companies, 1905, p. 237.

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range of flicker as the frequency is increased; and the more marked flicker when the finer-filament lamps are operated at a given frequency. They indicate that the tungsten lamp is less adaptable for use upon low-frequency currents than the carbon lamp.

Experience indicates that while lighting from 25-cycle circuits is satisfactory for many purposes, yet is not entirely satisfactory for all classes of service with all sizes of lamps. This frequency appears to be just a little too low to be generally acceptable.

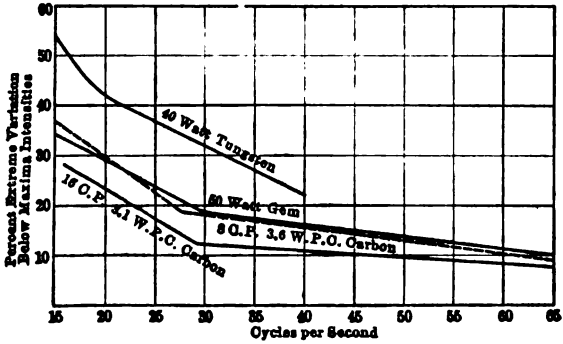


FIG. 8.—Flicker as indicated by cyclic candle-power variations.*

29. Limits of acceptability for multiple incandescent lamps. The measure of rating uniformity of incandescent lamps in respect to light intensity, energy consumption and efficiency is indicated by the limits of acceptability prescribed in the standard specifications.

Type (105 to 125 volts)	Rating	Tolerances	
		Watts	Lumens per watt
Tungsten—vacuum.....	40 watts	± 8 per cent.	± 6 per cent.
Tungsten—gas-filled.....	200 watts	± 18 per cent.	± 12 per cent.

The tolerances differ for gas-filled lamps of various sizes and are in general wider for smaller lamps and narrower for larger lamps.

30. Spherical reduction factor. It was formerly customary to measure and rate incandescent lamps in terms of mean horizontal candle power. As for most purposes the total light produced is the quantity to be considered, and as comparisons of efficiency can be made only on a basis of total light, the mean horizontal candle power has been superseded by the total lumens as an expression of light output. Occasionally, however, the relation of mean horizontal candle power is desired, and the spherical reduction factor or ratio of mean spherical to mean horizontal candle power is required. This for the oval filament carbon lamp is about 0.82. For the straight side bulb vacuum tungsten lamp it is about 0.78. As the mean horizontal candle power is not very significant in the case of gas-filled lamps no spherical reduction factor can be stated.

* Langmuir, I. "Flicker of Incandescent Lamps on Alternating Current," *G. E. Review*, 1914, p. 294.

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31. Brightness of light sources*

Source	Candle-power per sq. in.	Lamberts
Crater, carbon arc	84,000	40,900
Magnetite arc	4,000	1,950
Nernst glower (115-volt, 6-amp. d.c.)	3,010	1,460
Incandescent lamps:		
Tungsten, 1.25 watts per candle	1,060	516
Grapnitized carbon filament, 2.5 watts per candle	750	365
Tantalum, 2.0 watts per candle	580	283
Carbon, 3.1 watts per candle	485	236
Carbon, 3.5 watts per candle	400	195
Carbon, 4.0 watts per candle	325	158
Acetylene flame (1-ft. burner)	53	26
Acetylene flame (¼-ft. burner)	33	16
Welsbach mantle	31	15
Welsbach (mesh)	56	27
Cooper-Hewitt mercury vapor lamp	14.9	7.3
Kerosene flame	9.0	4.4
Gas flame (fishtail)	2.7	1.3
25-watt frosted tungsten lamp:		
Tip	1.67	0.8
Side	6.0	2.9
Additional data:†		
Flaming arc—clear globe		2,435
Tungsten filament of gas-filled lamp		1,400
Mercury vapor—quartz tube		487–292
Candle flame		1.5–1.9
Sky—daylight hours:		
With light clouds		2.0
Clouds predominating, generally cumulus		1.9
Blue predominating, clouds cirus		1.5
Cloudless, blue or hazy		1.0
Cloudy, storm near or present		0.7 or less

32. Life performance for the various lamp types is treated in Pars. 33 to 83. In general, however, the life is variable to a marked degree, and it is necessary to consider averages of large groups of lamps rather than the performance of a few samples before drawing conclusions concerning values. Also it is to be borne in mind that the only generally applicable statistics of performance are those obtained in a laboratory under reproducible and ideal conditions of operation. In service the performance may vary largely. All performance data given herein must be qualified to the extent that they may not be strictly applicable to a given set of operating conditions.

CARBON-FILAMENT LAMPS

33. Classification. Carbon-filament lamps may be classified according to filament characteristics under "untreated" (Par. **34**), "treated" (Par. **36**) and "metallized" (Par. **44**) lamps.

34. Untreated carbon filaments are now employed principally in sign lamps of the 10- and 20-watt sizes of the 110-volt range, and in lamps of the 220-volt range. As the filament has a higher resistance, it is shorter and may be disposed in a small bulb, where the longer treated filament cannot be utilized. As they are capable of only 30 to 40 per cent. of the useful life of treated-filament lamps, they are operated at a lower efficiency and are used only where necessary.

* Ives and Luckiesh. *Electrical World*, February 16, 1911.
† "Illuminating Engineering Practice," I. E. S., Univ. Penn. Lectures, 1916.

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35. Untreated carbon-filament lamps

Rated and average watts	Mean horizontal c-p.	Total lumens	Commercial rating, watts per mean horizontal c-p.	Specific consumption, watts per mean spherical c-p.	Specific output, lumens per watt	Average total life, hr.
105 to 125 volts						
10	2.0	21.2	5.0	5.88	2.12	2,000
20	4.8	51.2	4.15	4.88	2.56	1,000
200 to 260 volts						
35	7.95	84.0	4.40	5.24	2.40	1,000
60	16.26	170.4	3.69	4.40	2.84	750
120	32.52	340.8	3.69	4.40	2.84	750

36. The treated carbon filament (having a coating of graphitic carbon deposited by flashing in an atmosphere of hydro-carbon vapor) is the standard carbon filament employed in most lamps manufactured from 1893 to about 1908. The principal sizes and corresponding statistics appear in Par. **37.**

37. Treated carbon-filament lamps

Rated and average watts	Mean horizontal c-p.	Total lumens	Commercial rating, watts per mean horizontal c-p.	Specific consumption, watts per mean spherical c-p.	Specific output, lumens per watt	Average total life, hr.
20	4.82	50.4	4.15	5.05	2.52	1,500
30	9.29	96.0	3.23	3.91	3.20	1,050
50	16.83	174.5	2.97	3.61	3.49	700
60	20.20	209.4	2.97	3.61	3.49	700

38. Treated carbon-filament lamps. This form of lamp beginning with 1894 was the principal illuminant for electric lighting service until displaced by the Mazda lamp. It possessed the qualities of reliability, simplicity, and ruggedness to a marked degree, failing only to produce light as efficiently as its modern competitor. Its sterling qualities have continued it in service in considerable quantities. Fig. 9 shows for a typical treated carbon-filament lamp the performance throughout useful life, illustrating after an early adjustment period the gradual decline in watts due to increase in filament resistance, the falling-off in candle-power due to decreased wa

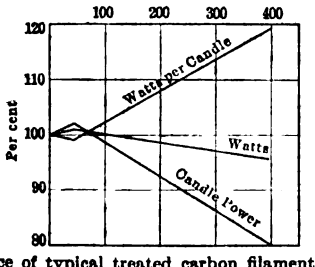


FIG. 9.—Performance of typical treated carbon filament lamp throughout life.

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and blackened bulb and the consequent increase throughout life in the watts per candle.

39. Candle-power performance curves of typical high-grade treated carbon filament lamps are given in Fig. 10, being a combination of curves published by several lamp manufacturers from independent tests of their products.

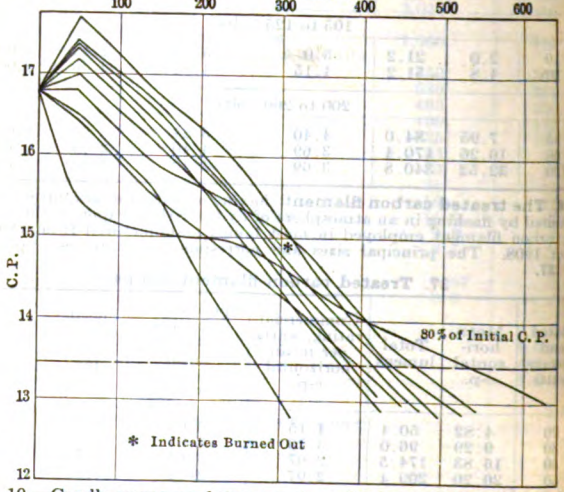


FIG. 10.—Candle-power performance throughout useful life of a typical group of treated carbon-filament lamps.

40. Candle-power deterioration throughout life is due in approximately equal parts to decrease in watts occasioned by increase in filament resistance and to increase in absorption of light due to bulb blackening.

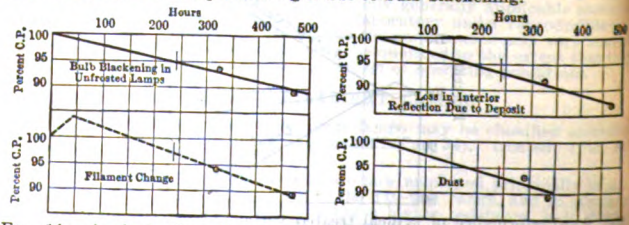


FIG. 11.—Analysis of candle-power decline in frosted carbon-filament lamps.

41. Frosted carbon-filament lamps decline in candle-power at about twice the rate of clear lamps. An analysis of the cause of such decline appears in Fig. 11.*

* Hyde, E. P. *Electrical Review*, 1907, p. 556.
Millar, P. S. *Electrical World*, 1907, p. 798.
Kennelly, A. E. *Electrical World*, May 18, 1907.

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42. Performance on direct current compared with alternating current. So far as is known there is no material difference between the performance of carbon lamps on direct current and on 60-cycle sine-wave current.

43. Status of carbon-filament lamps. By reason of their ruggedness and low cost, treated carbon-filament lamps continue to command a considerable sale. Where theft or breakage is apprehended, or when cost of power is very low, carbon-filament lamps may often be used to advantage. In 1919 all forms of carbon-filament lamps aggregated about 7 per cent. of the total incandescent lamps sold in this country.

44. Metallized carbon filament (Gem) lamps are so called because the temperature coefficient throughout the ordinary range is positive. As the specific resistance of the filament is lower than that of the treated carbon filament, a longer, finer and therefore more fragile filament is necessitated. This lamp is about 20 per cent. more efficient than the treated carbon-filament lamp. Being inferior to the treated carbon-filament lamp in ruggedness and inferior to the Mazda lamp in efficiency, it was practically abandoned in 1918 after having served a useful purpose in bridging the gap between the carbon and tungsten filament lamps.

Sizes of metallized carbon-filament lamps ranged up to 100 watts. Efficiencies were of the order of 4 lumens per watt with a total average life of about 700 hr.

45. Relative annual demand for incandescent lamps of various types. Fig. 12 depicts the history of sales of various types of incandescent lamps as reported by the Lamp Committee of the National Electric Light Association. The metallized carbon-filament (Gem) lamps which filled an appreciable share of the demand in 1907 were employed principally by central stations in their customers' service. The final abandonment of the lamp in 1918 was brought about by the necessity for eliminating inefficient lamps during the war. The growth of the tungsten filament (Mazda) lamp has been consistent from the start, a dominating position having been attained in 1912.

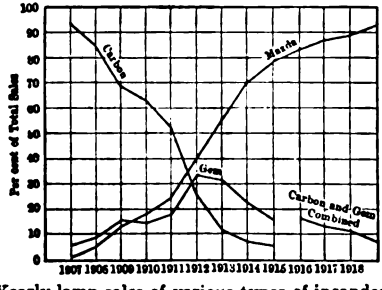


FIG. 12.—Yearly lamp sales of various types of incandescent lamps.

TANTALUM FILAMENT LAMPS

46. The tantalum filament lamp antedated the tungsten lamp but failed of complete success because of the advent of the latter. Due to serious crystallization and offsetting of the filament when operated upon alternating current, its use was practically restricted to direct-current operation. Used upon alternating current of 60 cycles, its life was only about one-quarter of that upon direct current. Upon lower frequencies the life was somewhat better.*

The tantalum lamp attained to large use in Germany where it was developed, but did not come into general use in America. The filaments were

* Sharp, C. H. *Transactions* A. I. E. E., November 23, 1906.

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imported by American manufacturers who placed the lamp upon the market in 1906. Sizes ranged from 25 to 80 watts. Efficiencies were of the order of 5.5 lumens per watt. The average life of 40-watt lamps on direct current was about 600 hr.

TUNGSTEN-FILAMENT LAMPS (VACUUM TYPE)

47. Early processes of filament manufacture. The earliest successful manufacture of tungsten-filament lamps was in 1906. There were three pioneer processes of filament manufacture, as follows: (a) that of Just and Hanaman, who deposited tungsten upon a very fine carbon-filament core afterward removing the carbon and sintering the tungsten; (b) that of Kuzel, who produced a colloidal solution of tungsten, and after bringing it to a suitable consistency squirted it to the desired diameter, and sintered it; (c) that of Von Welsbach (after the osmium process) who prepared a paste of finely divided tungsten mixed with an organic binder, and squirted it. The thread thus formed was reduced and sintered.

48. Early American manufacture. Tungsten-filament lamps were produced commercially in America early in 1907. These were made by the Welsbach process. The lamps made by the General Electric Company corresponded to the Osram lamp as produced by the Auer Company in Berlin. Those made by the Westinghouse Lamp Company followed the processes and construction adopted for the Osmin lamp by the Osmium Lamp Company of Vienna. The earlier styles and sizes in which the tungsten lamp was made available were complementary to carbon-filament lamps. Thus the larger sizes of multiple (100–130 volt) lamps were produced beginning with the 100-watt size for multiple circuits. This most happily introduced the lamp in a manner which led to gradual and constructive replacement of its less efficient predecessors. The development of the smaller sizes followed, as shown in Par. **49**.

49. Beginning of commercial use of Mazda lamps in the United States

Watts	Pressed filament	Drawn wire	"Getter"* introduced
10	.....	1912	October, 1913
15	.....	November, 1911	October, 1913
20	January, 1910	April, 1912	October, 1913
25	October, 1908	February, 1911	October, 1913
40	June, 1908	February, 1911	October, 1913
60	April, 1908	March, 1911	Sept., 1912
100	October, 1907	March, 1911	May, 1912
150	During 1909	March, 1911	October, 1911
250	During 1909	March, 1911	October, 1911
400	During 1910	During 1911	During 1911
500	During 1909	During 1911	During 1911

50. Fragility of early types. These pressed or squirted filaments were quite brittle when cold. They were mounted as short hairpin loops, held rigidly at or near the loop. In the smaller sizes particularly it was necessary to observe great precaution in order to avoid filament breakage in shipment, and even after installation.

51. Fragility reduced. The quality of the lamps was improved rapidly, and, to some extent, the early fragility was overcome. The ruggedness of a tungsten lamp depends chiefly upon the strength of the filament, and upon the manner in which the filament is mounted. The first notable event in the direction of ruggedness was the development of a long pressed filament wound continuously upon an arbor in a manner not dissimilar to that previously adopted in the tantalum lamp. The filament ends, however

* See Par. **57**.

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were attached to the lead wires in a special manner which contributed to the ruggedness of the lamp.*

52. Drawn wire. This was followed shortly by the announcement that tungsten wire had been drawn, and that drawn-wire tungsten lamps had been made successfully. Wire thus drawn was perfectly ductile, but, in the process of exhausting the bulbs and burning for a short time in the factory, much of the ductility was destroyed. Nevertheless, by employing a long filament of this wire, wound continuously as in the tantalum lamp, a much stronger tungsten lamp was achieved than previously had been available. Some idea of the increase in strength of the filament itself is given by the diagram in Fig. 13.†

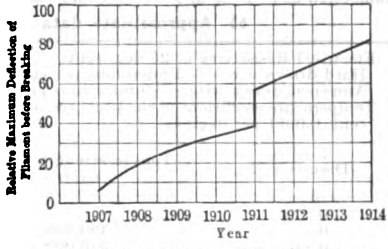


FIG. 13.—Increasing strength of tungsten filaments.

53. Modern manufacture of tungsten lamps. "The raw material used in the filament factory is a concentrated ore of tungsten, from which pure tungstic oxide, a fine-grained yellow powder, is obtained. This is 'doped' and reduced to tungsten metal by hydrogen in an electric furnace; the metal produced being in powder form, rather coarse grained, gray in color, and very heavy. This tungsten powder is formed into ingots about ¼ in. square and 6 in. long, by pressure alone, no binder being used. The pressure, which is very great, is applied transversely and compacts the tungsten so that the ingot can be handled. It is then placed in an electric furnace in an atmosphere of hydrogen and heated to a white heat, the effect of this heat being to compact and strengthen the ingot and make it a good conductor of electricity. The ingot is then placed in an atmosphere of hydrogen and heated to near the melting point, long enough to thoroughly sinter the ingot. The ingot now has a high luster, and the powder particles of which it is composed are welded together quite firmly. The square ingot now goes to a swaging machine. It is heated to white heat, taken out into the open air and swaged. During this operation a cloud of tungstic oxide rises from the ingot. The ingot is reheated and swaged several times before the square ingot becomes round. The heating and swaging are continued until the ingot is changed to a rod, 3/100 in. in diameter and 30 ft. long. Before this, when the rod is about 5/100 in. in diameter, it begins to have a fibrous structure. At 3/100 it has a well-developed fibrous structure, but can easily be broken by bending back and forth once or twice.

From thirty mils the rod or wire is reduced in size by hot drawing through diamond dies. The wire is heated to a bright red heat and is still red hot after passing through the die. This degree of heating is continued until the wire is only three mils in diameter, which is about the size of the filament in a 100-volt, 100-watt lamp. Below this, the temperature of drawing is reduced and the last drafts of any wire are made below red heat. The wire is now quite ductile and the last drafts may be made cold if desired. During this drawing the wire is lubricated with graphite, which forms a coating and prevents oxidation of the wire. It also lubricates the wire when it passes through the die. The last draft is made through a very perfect die which reduces the diameter of the wire very slightly, and in this way very long pieces are made which are the same size throughout."‡

Wire so produced is cut accurately to length and is wound upon the filament supports. A bulb-blackening preventive is introduced. After

* Scott. "A New form of Tungsten Lamp," Proceedings National Electric Light Association, May, 1910."

† "Recent Progress in the Art of Lamp Making" by Randall and Edwards, National Electric Light Association, 1913.

‡ J. W. Howell. *General Electric Review*, March, 1914.

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being sealed into the bulb, the lamp is placed upon the pumps and while being heated to a high temperature the bulb is evacuated. During the exhaustion process, the passage of current through the filament is reduced to a minimum. The candle-power of a lamp so produced is slightly lower than its rated or initial value. A brief "aging" brings it to or nearly to its true initial value.

54. Photometry. The process of manufacture has now been standardized so thoroughly that lamps of standard sizes are made accurately and are not photometered, though samples of each run are usually photometered as a check upon the manufacturing.

55. Approximate data on tungsten *

Electrical Resistivity at 25 deg. cent.
Hard drawn wire—6.2 microhms per cm. cube.
Annealed drawn wire—5.0 microhms per cm. cube.
Temperature coefficient of electrical resistivity between 0 deg. and 170 deg. cent. 0.0051 per degree.

Diameter (in.)	Tensile strength (lb. per sq. in.)	Specific gravity
0.150	.....	19.30
0.005	490,000	.....
0.0029	530,000	.....
0.0015	600,000	20.19

56. Current inrush. Tungsten has a positive-temperature coefficient, and the resistance is relatively low when the filament is cold. This results in a marked inrush of current when the lamp is lighted. For illustrative data, see Fig. 14.†

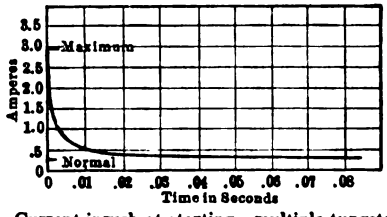


FIG. 14.—Current inrush at starting—multiple tungsten lamp.

57. "Getters."‡ The candle-power maintenance of tungsten lamps has been improved by the introduction of **bulb-blackening preventives** which to a marked extent diminish loss of light due to bulb blackening. These include substances which appear to react chemically with the tungsten which is evaporated from the filament, forming a nearly transparent deposit; and substances which are said to unite with the evaporated tungsten, forming a product which is decomposed by the incandescent filament, depositing the tungsten again upon the filament. Prior to the application of these materials the candle-power maintenance of the larger lamps left much to be desired. The bulb blackening preventives have been most efficacious in these larger sizes.

58. The growth of the use of tungsten lamps is shown in Fig. 12, sales of carbon and Gem lamps being shown for a comparison.

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* *Transactions* American Institute of Electrical Engineers, May 17, 1910, p. 957.
† Amrine and Guell. University of Illinois, Bulletin No. 33.
‡ Langmuir. *Trans.* A. I. E. E., 1913, p. 1913.

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59. Classification of principal tungsten vacuum lamps

	Watts	Volts
Sign lamps	2½	10–13
	5	10–13
	5	50–65
	10	100–130
General lighting	10	100–130
	15	100–130
	25	100–130
	40	100–130
	50	100–130
	60	100–130
	100	100–130
	25	200–260
	40	200–260
	50	200–260
	60	200–260
	100	200–260
Mill type	25	100–130
	50	100–130
	25	200–260
	50	200–260
Electric street railway service	23	105–130
	36	105–130
	56	105–130
	94	105–130
Train lighting service	10	30–34 and 60–65
	15	30–34
	20	30–34
	25 and 50	30–34
Country home lighting service	5	28–32
	10	28–32
	20	28–32
	40	28–32

The distribution of quantities of lamps by **voltage ranges** is as follows:

Voltage ranges	Per cent. lamp sales	Voltage ranges	Per cent. lamp sales
110–125 volts	85.1	Street railway	3.3
220–250 volts	5.1	30 and 60 volts	4.5
Street series	1.4	Miscellaneous	0.6

60. Rating. Tungsten-filament lamps for multiple circuits are rated in watts. It is the practice to maintain the watts of lamps at standard figures and to adjust the candlepower whenever improvements in lamp manufacture warrant increasing lamp efficiencies.

The rating of a batch of Mazda B lamps made under one set of manufacturing conditions is likely to be very close and consistent, while the rating of another batch may be slightly different. In Fig. 15 there is shown in the form of a target diagram the rating of 40-watt lamps taken from several manufacturing batches, all intended for an efficiency of 9.24 lumens per watt.

The target represents tolerances for watts and efficiency as set forth in the Standard Specifications for Incandescent Lamps. Each dot indicates by its location the lumens and watts of a sample lamp. These are "initial"

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values ascertained after the lamps have been "seasoned" by burning a labeled volts for about 1 hr.

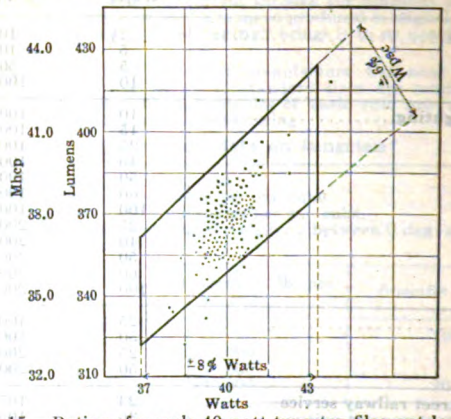


FIG. 15.—Rating of sample 40-watt tungsten-filament lamps.

61. Efficiency Rating of Mazda (Tungsten) Vacuum Lamps

Rating (watts)	Total lumens	Lumens per watt	Mean horizontal candle-power
10 (sign)	70	7.02	7.1
15	125	8.32	12.7
25	226	9.04	23.1
40	370	9.24	37.7
50	472	9.45	48.0
60	575	9.59	58.8
100	995	9.97	102.0

62. Conduction losses. The tungsten filament being long, is supported at a number of points throughout its length. At each point of support the filament is cooled by conduction. The loss of efficiency resulting from such cooling is appreciable. Tests of an early type of tungsten lamp* showed this loss to be about 7 per cent. In lamps of later construction, due to the employment of finer supports, this loss has been much reduced.

63. Average life. The average life of the standard multiple Mazda lamp is stated to be 1,000 hr. This means that the average of a group of lamps burned under correct operating conditions will be about 1,000 hr. As improvements have been effected in the lamps the manufacturers have increased the efficiency in order to adhere to the 1,000-hr. standard. The best general guide to the useful life of American lamps is to be found in the published data of the lamp manufacturers.

As compared with life in the laboratory under operating conditions, performance in service may differ widely. Breakage and line pressure fluctuations tend to make the life shorter. Line potential drop with resultant operation below correct voltage often tends to make life longer.

64. Life evaluation.† The term "useful life" is applied to the hours to 80 per cent. of initial candle-power or to earlier failure. Eighty per cent.

* Hyde, Cady and Worthing. *Transactions* I. E. S., 1911, p. 258.
† Millar and Lewinson. *Transactions* I. E. S., 1911, p. 744.

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is an arbitrary measure of effectiveness applied by common consent in the interests of good maintenance of illuminating power. The significance and the place of the 80 per cent. criterion in life evaluation may be noted in Fig. 17 which shows that the smaller multiple lamps fail well within the 80 per cent. limit, while the larger lamps continue in service long after the 80 per cent. line has been passed.

65. Life performance. In Fig. 16 typical performance of a 40-watt Mazda lamp throughout useful life is shown. This is characterised by a gradual decline in illuminating power and a gradual decrease in watts with corresponding decrease in efficiency.

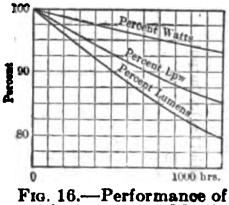


FIG. 16.—Performance of typical 40-watt Mazda lamp.

Mazda lamps when shipped from manufactories are only partly "seasoned." In this condition the filament resistance is a little below normal. The resultant higher watts of multiple lamps is accompanied by slightly low light output and of course the efficiency is low. Operation at labeled volts for about 1 hr. brings the lamps to normal "initial" condition. This 1-hr. seasoning process is not shown in the diagram.

66. Life performance; various sizes. The change in illuminating power and watts during life is shown in Fig. 17. In general the rate of decline of light output of Mazda lamps at operating efficiencies is smaller, but failure occurs earlier in the smaller sizes. In order to diminish the differences in life resulting from this characteristic, the smaller lamps are operated as shown at somewhat lower efficiencies than the larger lamps (61). The performance data in this figure are at prevailing efficiencies and show operation upon 60-cycle circuits in the laboratory. The curve for lamps of a given size represents the performance of a typical lamp continued to average ultimate life under laboratory conditions. Individual lamps of course fail after a shorter or longer period of burning than this average (67). The average curves of per cent. change in watts through life for the various sizes of lamps are so similar that they may be represented by a single line.*

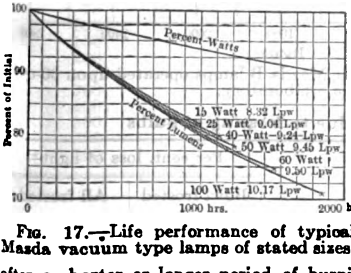


FIG. 17.—Life performance of typical Mazda vacuum type lamps of stated sizes.

67. Influence of external temperature upon the performance of lamps. But little information is available on this subject. Among carbon-filament lamps it has been found that relatively high external temperatures (200 deg. fahr.) result in a few poor vacuum lamps, which "slump" in candle-power. This presumably is due to the water vapor expelled from the glass at the higher temperature. Among Mazda lamps more care is taken to eliminate water vapor, and this effect, not very serious among carbon lamps, should be less noticeable in the performance of Mazda lamps.

68. Influence of the character of current supply upon the performance of tungsten-filament lamps has not been studied as extensively as the importance of the subject warrants. Tests of the Lamp Committee of the Association of Edison Illuminating Companies have shown that operation upon circuits supplied with 60-cycle sine wave current results in a slightly higher mortality rate coupled with a slightly better candle-power maintenance than is experienced when the lamps are operated upon direct current. The one effect just counterbalances the other so that the useful life is not greatly different on direct and on alternating current.

* All performance data of lamps are available through the courtesy of the Lamp Committee of the Association of Edison Illuminating Companies.

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69. Mortality rate. The diagram in Fig. 18 shows the mortality rate of 40-watt Mazda B lamps operated at rated initial efficiency upon 60-cycle current in the laboratory. Each dot indicates by reference to the scale of abscissæ the hours at which a lamp failed, and by reference to the scale of ordinates the approximate illuminating power just before failure. In lamps of smaller sizes the failures tend to take place after shorter periods of burning. Among lamps of larger sizes the reverse order prevails.

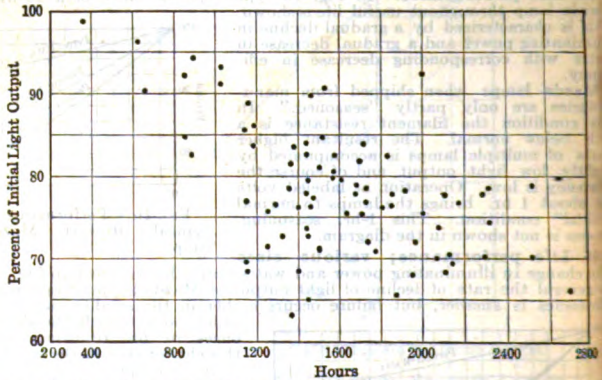


FIG. 18.—Mortality rate of 40-watt Mazda B lamps operated upon 60-cycle circuits in a laboratory.

70. Loss of light due to frosting of bulbs

	Per cent. loss of light*	
	Bowl frosted	All frosted
Straight side bulbs, 25 to 250 watts	3	8
Round bulbs, 25 to 40 watts	5	8

71. Voltage fluctuations of equal amplitude and duration above and below the mean result in shorter lamp life than would be obtained in operation at the same mean voltage steadily maintained.

72. Linolite lamps are a special form of tubular lamps particularly adapted for use in lighting show-cases, and other spaces for which their dimensions are favorably adapted. No data are available as to the relative life of such tubular lamps and ordinary bulb lamps at a given efficiency.

TUNGSTEN FILAMENT LAMPS FILLED WITH INERT GAS

73. General effects of the gas.† As a result of work of the Research Laboratory of the General Electric Company it has been found that inert gas within the bulb of a tungsten lamp operates to: (*a*) cool the filament; (*b*) reduce the rate of evaporation; (*c*) convey the evaporated material to the top of the bulb. The problem of increasing the efficiency of tungsten lamps

* Courtesy Edison Lamp Works.
Hyde, *Electrical Review*, April 6, 1907.
Millar, *Electrical World*, Vol. XLIX, p. 798.

† Langmuir. *Transactions* American Institute Electrical Engineers, October, 1913.
Langmuir and Orange. *Transactions* American Institute Electrical Engineers, October, 1913.

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—at least those having stouter filaments—is that of avoiding bulb blackening, which is the life-limiting feature.

The cooling effect of an inert gas decreases the candle-power of the filament, and in this respect the gas is detrimental. To obtain the same efficiency as in a vacuum it is necessary to increase the watts and operate the filament at a higher temperature. On the other hand the gas pressure reduces the rate of evaporation, and the convection currents set up within the bulb deposit in the upper part of the bulb such tungsten as may be evaporated. The cooling effect is greater, of course, in the case of the smaller-diameter filaments. In fact, among the smaller sizes of lamps for multiple circuits the cooling effect is so great that these do not benefit by this improvement. Among filaments which operate at greater current values, the disadvantage of the cooling effect is more than compensated by the advantages listed above. The stouter the filament the greater the benefit derived and the higher the efficiency at which it can be operated without decreasing the life.

74. Efficiency. The efficiency ratings of Mazda "C" lamps as of January, 1920, are shown in the following table. In comparison with other high-power illuminants it must be remembered that these lamps are rarely used bare and that allowance must be made for the loss of light in fixtures

Efficiency rating—gas-filled lamps

Multiple lamps

Watts	Lumens	Lumens per watt
50 (white)	450 (approximately)	.....
75	865	11.53
100	1,260	12.57
150	2,040	13.66
200	3,100	15.51
300	4,840	16.11
400	6,700	16.76
500	8,750	17.45
750	13,900	18.48
1,000	19,300	19.33

Series lamps

Amperes	Nominal candle-power	Lumens	Average volts	Average watts	Lumens per watt
5.5	60	600	8.9	48.7	12.32
	80	800	10.9	59.9	13.37
	100	1,000	13.0	71.6	13.96
	250	2,500	29.7	163.0	15.32
	400	4,000	47.4	261.0	15.32
6.6	60	600	7.4	49.2	12.20
	80	800	9.2	60.5	13.23
	100	1,000	10.9	71.6	13.96
	250	2,500	23.5	155.0	16.11
	400	4,000	37.6	248.0	16.11
	600	6,000	56.4	372.0	16.11
7.5	60	600	6.8	50.6	11.86
	80	800	8.2	61.1	13.09
	100	1,000	9.6	71.6	13.96
	250	2,500	21.2	159.0	15.71
	400	4,000	33.1	248.0	16.11
	600	6,000	48.4	363.0	16.53
15.0	400	4,000	14.9	223.0	17.95
20.0	600	6,000	16.0	320.0	18.76
	1,000	10,000	25.9	517.0	19.33

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75. Sizes and types. This improvement in tungsten-filament lamps is applied to multiple 110-volt lamps of 50 watts and larger, to all sizes of street series lamps of 3.5 amperes and greater, and to low voltage lamps of 1.5 amperes. Its most conspicuous result has been the extension of the incandescent lamp into the higher power illuminant field formerly occupied exclusively by the arc lamp.

The principal types of gas-filled lamps are as follows:

Multiple service		Street series service	
Watts	Volts	Lumens	Amperes
75	100–125	600	5.5
100	100–125	600	6.6
150	100–125	600	7.5
200	100–125	800	7.5
300	100–125	1,000	7.5
400	100–125	2,500	7.5
500	100–125	4,000	7.5
750	100–125	6,000	6.6
1,000	100–125	6,000	7.5
		4,000	15.0
200	220–250	.....	.....
300	220–250	6,000	20.0
400	220–250	10,000	20.0
500	220–250		
750	220–250	Country home lighting service	
1,000	220–250	50	28–30
		75	28–30
		100	28–30

76. The construction of tungsten gas-filled lamps of various sizes is illustrated in Fig. 19, featuring the concentrated filament and the bulb designed to promote location of the light-absorbing deposit in a small neck near the base, where its absorption will be at a minimum. In lamps of different makes the filaments are sometimes arranged somewhat differently.

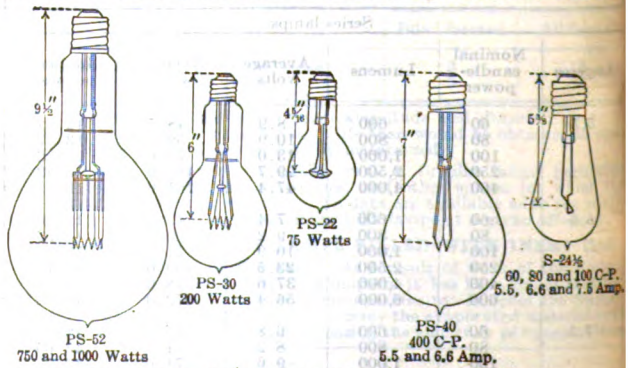


FIG. 19.—Illustrating construction of Mazda "C" lamps.

77. Rating multiple lamps. The target diagram in Fig. 20 shows the rating of samples taken from various packages of 200-watt Mazda "C" lamps. The prevailing efficiency rating for these lamps is 15.1 lumens per watt. The trapezoid represents the tolerances of the Standard Specifications. Each dot shows the lumens and watts of one lamp.

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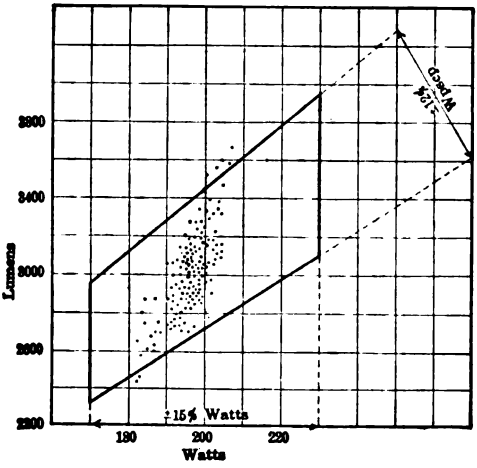


FIG. 20.—Typical rating of tungsten filament gas-filled multiple lamps.

The **rating tolerances** of the Standard Specifications are as follows:

Multiple Mazda "C"	Watts, per cent.	WPSCP, per cent.
75 watts	± 18	± 15
100 watts	± 18	± 12
150, 200 and 300 watts	± 15	± 12
400–1,000 watts inclusive	± 12	± 12

78. Rating series lamps. Series lamps are expected to fall within the following tolerances.

Series Mazda "C"	SCP, per cent.	Watts, per cent.
5.5, 6.6, 7.5 amp., 60-c-p	± 15	± 13
5.5, 6.6, 7.5 amp., 100-c-p	± 14	± 11
5.5, 6.6, 7.5 amp., 250-c-p	± 14	± 10

79. Life performance. For the 200-watt Mazda "C" lamps representative performance curves are shown in Fig. 21, illustrating the decrease in lumens, watts and efficiency throughout life.

80. Filament ruggedness. In general the larger lamps are more sturdy than the smaller ones. In all types new lamp filaments are more rugged than those which have been operated for some time. Among the smaller sizes of lamps the filaments become quite fragile after a few hundred hours burning.

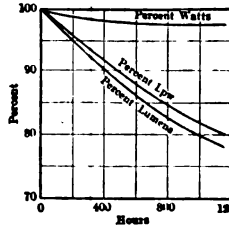


FIG. 21.—Typical performance curves of 200-watt Mazda "C" lamps.

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81. Descriptive classification of types

Conventional description	Nature of electrodes	Types of lamp	Chief light production from	Methods of light production
Carbon-arc.	Pure carbon.	Open, Enclosed, Intensified.	Incandescent electrodes.	Principally incandescence of electrode ends—some little light from arc by luminescence.
Flame-arc.	Mineralised carbon.	Short burning. Long burning.	Luminous arc.	Selective radiation from vapors or gases which are in arc stream as result of vaporization from electrodes, especially from the anode. Some little light from incandescent electrode ends.
Magnetite and luminous arcs.	Metallic.	Regular Ornamental (inverted).	Luminous arc.	Luminescence of arc into which light-giving elements are brought from cathode by electro-conduction.

NOTE.—All lamps have been developed commercially in alternating-current types as well as in direct-current types except those of the third group.

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82. Mortality rate. The rate of burn-out of 200-watt Mazda "C" lamps is shown in Fig. 22, each dot indicating time of failure and illuminating power just before failure.

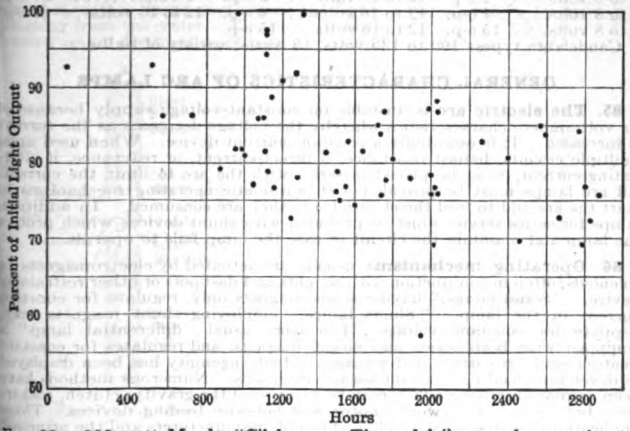


FIG. 22.—200-watt Mazda "C" lamps. Time of failure and approximate light output just before failure.

83. Miscellaneous forms of tungsten-filament lamps. In its gas-filled form the tungsten-filament lamp has been applied to a wide variety of uses for which the incandescent lamp formerly has not served satisfactorily. Included among these are projector lamps for searchlights and floodlights and for moving picture apparatus, in all of which forms the lamps are operated at relatively high efficiencies, yielding relatively short lives.

An illustration of the latest form of motion picture Mazda "C" lamp is shown in Fig. 23.

84. Miniature lamps. The tungsten filament gave great impetus to the use of incandescent lamps, in miniature form. Flashlamps, Christmas-tree lamps, automobile lamps, etc., have been developed with pronounced success. More recently the gas-filled tungsten lamp has displaced and is continuing to displace the vacuum type in several miniature classes. Space does not permit discussion of the miniature lamp, which though a product of tremendous and growing importance, yet involves special engineering features somewhat removed from those of general lighting practice.

The principal classes of miniature tungsten-filament lamps are as follows: For flash-light service, 0.3 amp.—2.5, 2.7, 2.9, 3.8 and 6.2 volts; for service with single-cell dry battery, 0.6 amp.—1.5 volts; for service with 2-cell dry battery, 0.8 amp.—2.7 to 3.0 volts. For automobile service

900 W. 30 A. Motion Picture

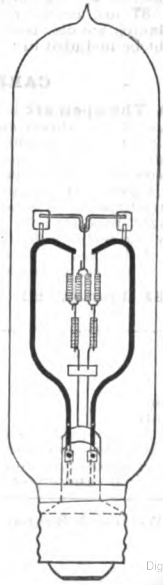


FIG. 23.—Mazda "C" motion-picture lamp.

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Vacuum lamps		Vacuum lamps		Gas-filled lamps	
3 to 4 volts....	2 c-p.	9 volts.....	18 c-p.	6 to 8 volts...	21 c-p.
6 to 8 volts....	2 c-p.	12 to 16 volts...	2 c-p.	9 volts.....	27 c-p.
6 to 8 volts....	4 c-p.	12 to 16 volts...	4 c-p.	12 to 16 volts...	21 c-p.
6 to 8 volts....	15 c-p.	12 to 16 volts...	15 c-p.		

Candelabra types: 100 to 125 volts, 15 watts; variety of bulbs.

GENERAL CHARACTERISTICS OF ARC LAMPS

85. The electric arc is unstable on constant-voltage supply because of its volt-ampere characteristics whereby the voltage decreases as the current is increased. It is essentially a constant-current device. When used upon multiple circuits, ballast resistance, if direct-current, or reactance, if alternating-current, must be placed in series with the arc to limit the current. All arc lamps must be provided with automatic operating mechanisms to start the arc and to feed the electrodes as they are consumed. In addition, lamps for series service must be provided with shunt devices which protect the lamp and maintain the circuit in case the lamp fails to operate.

86. Operating mechanisms usually are actuated by electromagnets or solenoids, often in conjunction with weights and dashpots or other restraining device. "Series lamps," having series magnets only, regulate for constant current in the lamp. "Shunt lamps," employing shunt magnets only, regulate for constant voltage. The more usual "differential lamp" is equipped with both series and shunt magnets, and regulates for constant relation between current and voltage. Much ingenuity has been displayed in developing feeding mechanisms for arc lamps. Numerous methods have been employed, among which may be mentioned the gravity, clutch, rocker-arm, brakewheel, clockwork, motor and hot-wire feeding devices. These applications are described in publications of manufacturers and the principal methods are described in text-books.

87. Classification of arc lamps. Arc lamps may be classified in a number of ways according to the viewpoint. The classifications adopted in Par. **87** are comprehensive. In the following pages the several types of arc lamps are discussed in the order indicated. Vacuum tube lamps, which might be included in this class, are discussed later (Par. **116**).

CARBON-ELECTRODE ARC LAMPS

88. The open arc is now regarded as obsolete. In its most common form it was of the direct-current 9.6-amp. type—the old "full arc" to which the rating of "2,000 c-p.," was applied in earlier years. The arc is about $\frac{3}{8}$ in. (0.48 cm.) long and of low luminosity. The end of the negative (lower) electrode, after a few hours of burning, assumes a conical shape and yields some little light by incandescence. The end of the positive (upper) electrode becomes concave, and the "crater" thus formed is the chief source of light produced by the lamp, the process being that of incandescence. Only the feeble light from the arc itself is produced by luminescence. The end of the positive electrode becomes intensely hot, attaining at the hottest part of the crater to from 3,900 to 4,000 deg. cent.*

89. Photometric and electrical data on direct-current open carbon arc lamps

	"Full arc"	"Half arc"
Amperes	9.6	6.6
Watts	450	325
Mean spherical candle-power	410	240
Maximum candle-power	900 to 1,200	.....
Specific consumption—watts per candle	1.09	1.35
Nominal candle-power rating	2,000	1,200

* Weidner & Burgess. Bulletin Bureau of Standards, Vol. I, No. 1, 19.

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90. Light distribution from the open arc. Fig. 24 shows the open carbon arc.* It will be apparent at once that the lower electrode obstructs a large portion of the light emanating from the crater. The curve in Fig. 25 shows actual distribution of light compared

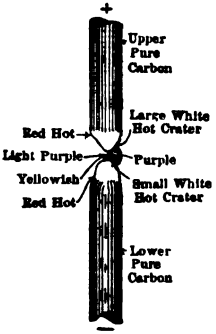


FIG. 24.—Open carbon arc.

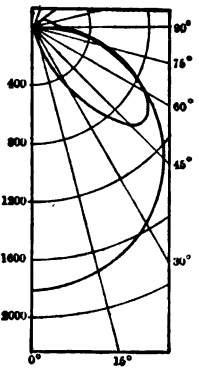


FIG. 25.—Distribution of light in vertical plane about 9.6-amp. direct-current open arc lamp. Also estimate of distribution if obstruction of lower electrode could be avoided.

with probable distribution if the lower electrode were transparent,† the difference illustrating the loss of light due to obstruction by the lower electrode.

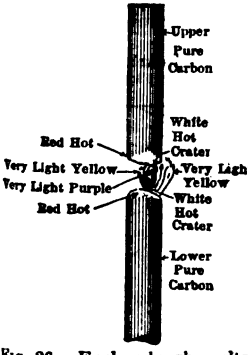


FIG. 26.—Enclosed carbon alternating-current arc.

91. Electrode life—open arc lamp. The open arc lamp suffered from short life of electrodes, unsteadiness of light, and poor light distribution. The electrode life was 7 or 8 hr. and it became common practice to employ two pairs of carbons, the second pair to replace automatically the first pair after these had been consumed, thereby securing continuous operation long enough for one night. These disadvantages were sufficient to occasion the general abandonment of the open arc lamp in favor of the enclosed carbon arc lamp which became available commercially in 1894.‡

92. The enclosed carbon arc lamp differs from the open arc in that the supply of air at the arc is restricted, thus retarding the rate of consumption of carbon, and securing an electrode life of 100–125 hr.; the arc is about ⅝ in. (0.95 cm.) long, requires from 70 to 80 volts, and adds appreciably to the violet light produced; the ends of the electrodes are nearly flat. The anode does not have a marked crater, and does not become so hot as in the open arc. Less light is produced per watt. A representation of the arc of an alternating-current enclosed lamp is given in Fig. 26.§ The enclosed arc lamp has been

*Blake and Couchey. "Arcs and Electrodes," *Gen. Elec. Review*, 1913 p. 497.

†Trotter. "Illumination—Its Distribution and Measurement," p. 147.

‡The Invention of the Enclosed Arc lamp—L. B. Marks, *Sibley Journal of Engineering*, Vol. XXII, 1907, p. 1.

§Blake and Couchey. "Arcs and Electrodes," *Gen. Elec. Review*, 1913, p. 497.

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manufactured in a wide variety of forms. Some of these with approxima data are listed in Par. 93.

93. Data on enclosed carbon arc lamps

	Auxiliary	Watts	Mean spherical candle-power	Watts per mean spherical candle-power	Power-factor
Series alternating current, 6.6-amp.	Opal inner and reflector	430	130	3.30	84
Series alternating current, 7.5-amp.	Opal inner and reflector	480	155	3.09	85
Series direct current, 6.6 amp.	Opal inner and reflector	490	260	1.88	...
Multiple direct current, 115 volts	Clear inner—opal outer	550	165	3.33	...
Multiple direct current, 115 volts	Clear inner—opal outer	715	240	2.98	...
Multiple alternating current, 115 volts	Clear inner—opal outer	430	145	2.97	70
Multiple alternating current, 115 volts	Clear inner—opal outer	540	190	2.84	70

94. Status of enclosed arc lamp. The enclosed arc lamp prov superior to the open arc lamp in (a) steadiness; (b) characteristic of lig distribution, and (c) electrode life. More effort was expended in develo ing it and equipping it with suitable glassware and, in the case of alternatin current lamps, with reflectors. In spite of its inefficiency, it prevailed ov the open arc lamps, and remained the standard lamp for street lighting un the advent of the metallic-electrode lamp.

95. Efficiency and light distribution—enclosed carbon arc lamp The efficiency of the arc is lower in the alternating-current type. Both ele trodes are raised to a high temperature, but neither attains the high tempera ture of the anode in the direct-current arc. The characteristics of light dis tribution from the two types of lamps appear in Fig. 27. It is general practice to equip the alternating-current lamps with a reflector which directs, below the horizontal, some of the light which would otherwise be distributed above the horizontal. The multiple lamps are less efficient than the series lamps. A certain amount of ballast is necessary and this accounts for the difference between the line voltage (100 to 120 volts), and the arc voltage (70 to 75 volts). If the circuit is for alternating current, a reactance is employed, which does not occasion a large wattage loss but reduces the power-factor. If a direct-current circuit, a resistance is used, which occasions a direct loss in watts.

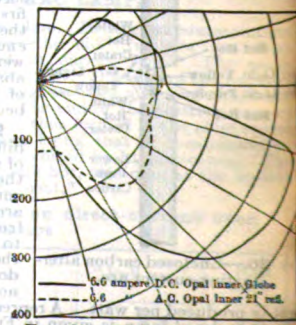


FIG. 27.—Light distribution in vertical plane about enclosed car bon arc lamps.

96. Intensified carbon arc lamps. The efficiency of a carbon arc lamp may be increased by diminishing the diameter of the electrodes with a given current or by increasing the current with given electrodes. In intensified

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arbon arc lamps the diameter of the carbons is reduced, producing a gain efficiency and a light which is more nearly white and steadier than that the ordinary enclosed arc lamp of which it is a refinement. Such lamps re used chiefly for lighting interiors where white light is desired, as in lothing stores. The intensified carbon arc was developed in Europe and xploited in small sizes operating at 2 and 3 amp., with an electrode life 20 hr. or less. In this country the developments were along the lines of omewhat larger lamps operating at higher currents and longer electrode fe. Typical lamps of this type are somewhat smaller than ordinary enclosed c lamps, and are designed for either direct-current or alternating-current rvice. Small-diameter electrodes (about 7 mm.) are used, and life of about hr. is realized. With opal globes an efficiency corresponding with approxiately 2 watts per mean spherical candle-power is obtained in the direct-rrent lamp. The General Electric Company has developed a lamp of this pe for direct-current service, in which two converging 6-mm. upper-positive rbons are used with a vertical lower carbon of 9.5 mm. diameter. This mp is somewhat larger and more substantially built than other lamps of the ass. The specific consumption when employed with an opal globe is ghtly more than 2 watts per mean spherical candle-power.

THE FLAME ARC LAMP

97. Short-burning flame arc lamp. The electrodes for short-burning ame arc lamps, consist commonly of carbon tubes packed with a mixture carbon and mineral salts. The anode is usually more highly mineralized an the cathode, in some cases the cathode is pure carbon. As a rule e electrodes are mounted in an inclined position illustrated in Fig. 28. eing long and of small diameter a copper wire is sometimes imbedded the carbon to add to its conductivity and mechanical strength. The arc rmed between the electrodes is arched ownward by means of a small mag-t. The arc is formed in a shallow p-like recess which becomes coated ith oxide which, being white, serves a good reflector. The inverted cup nfines the gases and retards oxida-on, reducing the rate of consumption,

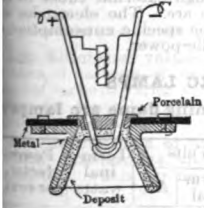


FIG. 28.—Short-burning flame arc and economizer.

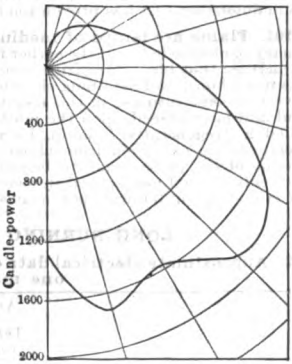


FIG. 29.—Light distribution in vertical plane about short-burning flame arc lamp with opal globe.

ence it is called the economizer. Fig. 29 shows the light distribution from typical short-burning flame arc lamp equipped with an opal globe. For is particular lamp the following data applies: yellow-light electrodes; mperes, 8; arc volts, 45; total watts, 440; mean spherical candle-power, 025; watts per candle, 0.43.

98. Nature of flame arc. Impurities in the carbon are detrimental in he arc lamp of types in which the chief light production is accomplished hrough the incandescence of the electrode ends. As carbon is the most

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refractory material known, impurities are always more volatile, and the presence tends to reduce the temperature of the electrode ends. Hence, in the manufacture of carbons for such lamps, purity is considered of first importance. In the flame arc, the purpose is to secure light from the arc rather than from the electrode ends. The carbon is impregnated with chemicals which, when volatilized and driven into the arc, become highly luminous. The lower temperature of the carbon ends, due to these impurities, is immaterial, since little dependence is placed upon the ends for light production. The flame arc is simply a carbon arc into which mineralized salts are introduced. These may be of calcium, for yellow light; of barium and titanium for white light; and of strontium, for reddish light. The carbon electrode serves as an electrical conductor and assures a hot and steady arc. The chemicals with which it is impregnated include those which are efficient light producers, and others whose functions are to promote high arc temperature and to steady the arc.

99. Theory of light production. The electrode ends, especially the anode, are brought to a high temperature, vaporizing the carbon and the metallic salts. The succeeding processes of light production are largely a matter of speculation at the present time. Some opinion favors luminescence as the process by which light is produced, other attributes it to favorable selective radiation from incandescent particles in the arc stream. An approved theory assumes the chemicals to become dissociated by the heat of the inner core of the arc (which is known to be hotter than the outer sheath) and to recombine in the outer sheath with evolution of heat, which tends to maintain the temperature of the arc. According to this view, the light is produced by luminous particles in process of combustion, which is a condition quite similar to that existing in ordinary flame.

100. Status of short-burning flame arc lamp. In this country the short-burning flame arc lamp has come into use chiefly for display lighting. Its maintenance cost has proven too high for most utilitarian purposes.

101. Flame arc lamps of medium electrode life. The obvious inadequacy of electrode life of the earlier forms of flame arc lamps led to attempts to increase that life. Magazine lamps have been devised having two to ten sets of carbons, and attaining electrode life of 30 to 40 hr. These, however, have not come into use in this country. The Jandus lamp devised in England and later placed upon the market in this country attains 70 hr. It is called a "regenerative" lamp, because the gases containing light-giving chemicals are conveyed from above the arc through external tubes to the bottom of the globe, again to be entrained in the arc. The electrodes are vertically coaxial and special in construction. The specific consumption of the lamp is about 0.6 watt per mean spherical candle-power.

LONG-BURNING FLAME ARC LAMPS

102. Approximate electrical data of long-burning flame arc lamps of one manufacture

	Amperes		Volts		Terminal watts	Power-factor, per cent
	Terminal	Arc	Terminal	Arc		
Alternating-current multiple 110-volt (compensator)	7.5	10.5	110	47	540	66
Alternating-current series.....	10.0	10.0	60	47	465	78
Alternating-current series (compensator)	7.5	10.0	86	47	500	78
Alternating-current series (compensator)	6.6	10.0	98	47	500	78
Direct-current multiple 110-volt.	6.5	6.5	110	67	715	.....

103. Life of electrodes. Carbons for enclosed flame arc lamps are usually of $\frac{1}{8}$ in. diameter and are 14 in. long. The unused portion of the upper is used for trimming the lower. A life somewhat in excess of 100 hr. is had

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The mechanism of an alternating-current enclosed flame arc lamp of one make is illustrated in Fig. 31.

104. General features. With the development of flame arc lamps which have an electrode life of 100 hr. or more, the flame arc has been placed in a position to compete with other illuminants for street-lighting service. In this type, electrodes of about ¼ in. (2.22 cm.) diameter are employed within a globe which restricts the air supply. It is known as the "long-burning" or "enclosed" flame arc. Long electrode life is secured at the expense of some efficiency. For this type of lamp, solid impregnated carbons have been developed in place of the familiar cored carbons employed in the original flame arc lamps. These are available in both yellow and white light forms, the latter being slightly less efficient. See Fig. 30.*

105. Electrical characteristics of flame arc lamps of one manufacture appear in Par. **104**. To adapt the alternating-current lamps for use upon various circuits, compensators are supplied, sometimes built in and sometimes external to the lamp proper.

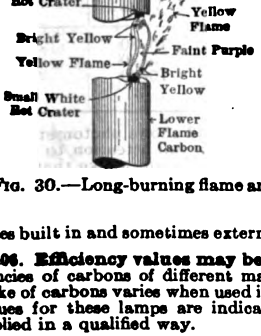


FIG. 30.—Long-burning flame arc.

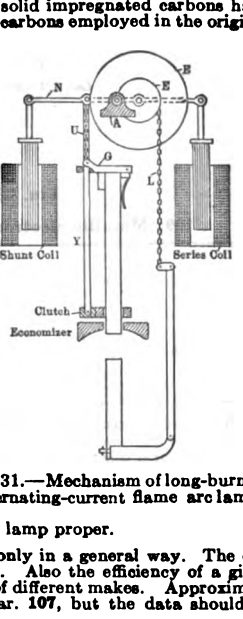


FIG. 31.—Mechanism of long-burning alternating-current flame arc lamp.

106. Efficiency values may be stated only in a general way. The efficiencies of carbons of different makes vary. Also the efficiency of a given make of carbons varies when used in lamps of different makes. Approximate values for these lamps are indicated in Par. **107**, but the data should be applied in a qualified way.

107. Efficiencies of 10-amp. long-burning flame arc lamps with "white" electrodes are as follows: Mean spherical candle-power, 700; watts, 520; watts per mean spherical candle-power, 0.74.

THE METALLIC-ELECTRODE ARC LAMP

108. Nature of arc and electrodes. This lamp differs radically from other arc lamps in that light is produced by luminescence of vapor brought into the arc stream by electro-conduction from the cathode. The arc of one form of this lamp is illustrated in Fig. 32.† The cathode consists of magnetic oxide of iron with titanium as the chief light-giving element, and other ingredients to serve as steadiers and vaporization retarders. The anode is of copper. The arc is fixed, and a small reflector is located advantageously within the lamp, directing downward and outward much of the light which

* Blake and Couchey. "Arcs and Electrodes," *Gen. Elec. Review*, 19,31 p. 497.

† Blake and Couchey. *Gen. Elec. Review*, 1913, p. 497.

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emanates from the arc in a direction above the horisontal. The metall electrodes are maintained at a relatively low temperature, and the arc w not re-establish itself every half cycle as with hot carbon electrodes. Th limits the lamp to operation upon direct current or rectified current.

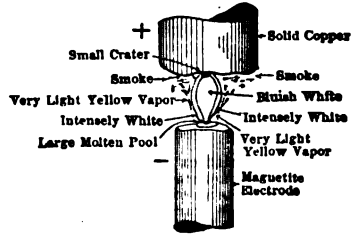


FIG. 32.—Magnetite arc.

109. Metallic electrode lamps for series circuits

Type	Approximate		
	Amperes	Volts	Watts
Magnetite	4.0	75–80	310
	5.0	75–80	400
	6.6	75–80	510
Metallic flame	4.0	73	290

110. Candle-power and efficiency. Par. 112 shows photometric dat on metallic-electrode lamps. The manufacturers call attention to the fa that the natural distribution of light from the arc is not unlike that from Mazda lamp, but that in adapting the lamp for commercial street lightin service, a reflector or refractor is placed over the arc, and the light distribu tion is modified as shown in two of the curves of Fig. 33 at the expense from 20 to 25 per cent. loss of light.

111. Light distribution characteristics. The distribution of lig about three types of magnetite arc lamps is shown in Fig. 33, manufacture data being employed.

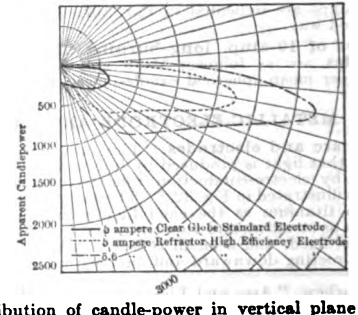


FIG. 33.—Distribution of candle-power in vertical plane about magnetit arc lamps.

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113. Magnetite lamps.

Recent improvements† in electrodes of the magnetite lamp make available increase of about one-third in either the efficiency or the hours per trim as may be desired. If a larger light output is desired it may be obtained without sacrifice of trimming period or increase of watts. If increase in output is not desired approximately the same illumination as that given by the standard electrodes may be had with reduction in watts which makes it possible to operate 60 lamps on a 50-light rectifier or 90 lamps on a 75-light rectifier with trimming periods increased by about one-third.

114. Regulating mechanism. In Fig. 34 are shown the essential regulating features of the magnetite lamp.‡ The electrodes are separated when

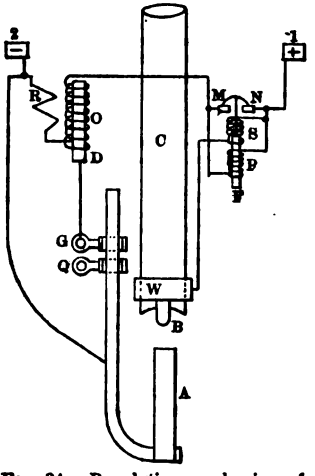


FIG. 34.—Regulating mechanism of magnetite arc lamp.

no voltage is applied at the lamp terminals. When the circuit is energized the electromagnet *O* raises its core *D*, bringing the lower or negative electrode *A* into contact with *B*, starting the arc. This closes the circuit through series coil *S* and short circuits *OR*, releasing *D* and allowing the lower electrode *A* to drop into its position as fixed by the clutch *Q*. As *A* is consumed, the shunt magnet *P* is strengthened, withdrawing core *F* until finally the shunt circuit *OR* is closed at *MN* and the arc is restruck. This mechanism regulates for constant arc length.

Approximate data at initial* operation

Circuit, amperes	Electrode	Equipment	Volts at terminal	Watts	Lumens	Lumens per watt	Hours per trim
4.0	Standard	Clear globe	75–80	310	3,220	10.4	350 (9½ in.)
	High efficiency	Clear globe	75–80	310	4,840	15.6	150 (9½ in.)
5.0	Standard	Diffusing globe	80	400	5,250	13.1	225 (9½ in.)
	High efficiency	Clear globe	75–80	388	8,000	20.6	125 (9½ in.)
6.6	Standard	Clear globe	75–80	510	8,400	16.5	125 (9½ in.)

* *Electrical World*, October 3, 1914, p. 661.

† Cameron and Halvorson, *Transactions* Illg. Eng. Soc., 1920.

‡ Steinmetz, "Radiation, Light and Illumination," p. 158.

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114. The ornamental magnetite lamp is a modification of the standar form, the regulating mechanism being placed below the arc. In efficienc and operating characteristics it is quite similar to the standard pendan lamp.

115. The titanium-carbide lamp was brought to an interesting sta of development in 1909, but did not enter into commercial practice.* I compared with the magnetite lamp it was of higher efficiency and was ava able in smaller units. It was withdrawn for further development witho having reached the commercial stage. No published description is ava able. It is understood, however, that with an electrode life of 100 hr. more, the lamp efficiency corresponds with about 0.65 watt per candle, distribution characteristic being similar to that of the magnetite lamp. T light is yellower than that of the magnetite lamp.

TUBE LAMPS

116. Vacuum arcs. The vacuum arc is essentially a constant curre device requiring regulation as does the open arc. Its volt ampere chara teristics differ from those of the open arc and are largely determined by t temperature of the arc and the resulting vapor or gas pressure. As usuall operated the voltage is constant throughout a range of current variation.

117. Low-pressure mercury arc. In the mercury vapor lamps th mercury cathode is vaporized as soon as the arc is struck. In the colum of vapor, formed within the tube and attaining a pressure of 1 to 2 mm. light is produced by luminescence, the arc being relatively cool, varyin from some 500 deg. cent. in the center to about 100 deg. cent. at the out surface of the glass tube. The anode located at the other end of the lam tube is of iron and operates at about 350 deg. cent.

118. Starting the mercury arc. In starting the lamp the arc may b struck by tilting the tube manually or automatically by an electromagne until a thin stream of mercury connects the two electrodes. When the tub resumes normal position breaking of this stream starts the arc. One alter native automatic starting which had superseded the above consists in shor circuiting a small current through inductance in series with the arc. Thi current is broken by a mercury switch or "shifter" magnetically operate by the induction coil. The resulting cathode discharge is sufficient to star ionization of the traces of mercury vapor in the tube and the arc forms To increase the effectiveness of the starting discharge a metallic coating o starting band is placed on the cathode bulb forming with the mercury inside a small condenser.

119. Alternating-current mercury arc. While the mercury-arc i essentially a unidirectional conductor it has been adapted for service o alternating current in the form of the mercury-vapor rectifier. The theory and operation of the commercial form of Cooper Hewitt lamps for single phase alternating current is indicated in Fig. 35. The cathode is connected to the middle of the secondary of an auto-transformer while the two anodes are connected to the ends. Thus the two halves of the autotransformer function alternately and the cathode is negative with respect to one or the other anode during the entire cycle. Enough reactance is used in series with the arc to maintain the current well above zero during the voltage alteration and the change in anodes. In order to keep the power factor high the balance of the current regulation on fluctuating voltage is secured by using resistance instead of reactance in series with the anode circuits.

120. Direct-current mercury arc. For operation on direct current reactance and resistance is connected in series with the arc, and adjusted for an arc voltage of about 75. The methods of starting are the same as for the alternating-current outfit.

121. Data on low-pressure lamps. The comparability of photometric data of mercury vapor lamps with those of incandescent lamps is open to ques tion. For what they may be worth photometric statistics are shown in the following table:

* Birge, "The Present Status of the Arc Lamp," *Proceedings* N. E. L. A. 1909.

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	Direct-current		Alternating current
	110	220	
Length of light-giving tube, inches	50	50	50
Terminal volts	110	220	110*
Amperes	3.5	3.5	3.8
Watts	385	770	430
Power factor per cent	.....	.....	85
Total lumens—bare	6,850	.....	.....
Total lumens—with reflector	5,487	9,430	6,129
Lumens per watt—bare	17.8	.....	.....
Lumens per watt—with reflector	14.3	12.1	14.3

122. Color. The light given off by the low-pressure vapor lamp is greenish-blue, and is without red rays (Fig. 4, Par. 8). Attempts have been made to correct this color by using other materials with the mercury and by combining the arc with incandescent lamps. Ives† reports that one candle-power mercury vapor light, mixed with 0.54 candle-power tungsten-lamp-light, yields a good subjective white light for general purposes. Hewitt has employed a flourescent paint to transform some of the radiation in the green portion of the spectrum into radiation of longer wave length. None of these devices appears to have achieved much success in practice.

123. Industrial use. The mercury arc has been found to be well adapted to certain kinds of industrial illumination. The large area of the light source and consequent low brightness affords an unusual degree of diffusion for an artificial source. The light is nearly monochromatic,

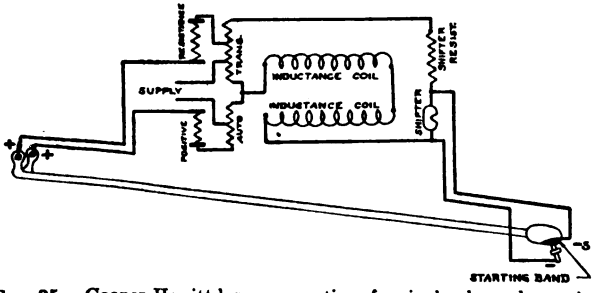


FIG. 35.—Cooper-Hewitt lamp connections for single-phase alternating current.

which practically eliminates chromatic aberration, resulting in high visual acuity. It serves advantageously in working and testing of machined metal surfaces and weaving of fine textured cotton and silk goods. The actinic efficiency per candle-power is three to four times that of ordinary incandescent light sources which gives the lamp a field of utility for high speed interior photographic work, including blueprinting, enlarging and photostat operation, as well as in moving picture studios.

124. Electrical data on high-pressure mercury vapor lamps

Direct-current supply	Burner volts	Current	Watts
110	90	4.0	440
120	175	3.5	770

* 220-volt lamps are available also.

† *Bulletin of the Bureau of Standards*, Vol. VI, p. 265.

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125. High-pressure mercury arc lamp. In order to take advantage of the higher efficiency obtainable at high vapor pressure an evacuated tube of fused quartz is used, as glass softens at a lower temperature than that required. The lamp is operated upon the same basic principles as underlie the operation of the low-pressure lamp. The cathode is of mercury and the anode is of mercury or tungsten. The quartz tubes (burners) are 5 to 10 in. long. The arc in quartz may be started by tilting manually or automatically as with the low-pressure arc. In starting, the current is about three times normal and the arc voltage is low, excess voltage being taken up by the ballast resistance. The lamp gives relatively little light, and that of a very green color. The current quickly vaporizes the mercury, increasing the vapor pressure and the resistance of the arc. Gradually a condition of normal operation is approached, and in about fifteen minutes current and voltage at the arc are at substantially the correct values. It is understood that lamps are being developed, or have been developed, for alternating-current service and for series service. A laboratory equipment is shown in Fig. 36. The mercury arc in quartz gives a light which is less pronouncedly green than that from the low-pressure arc. It is characterized by an abundance of ultra-violet radiation which the Bureau of Standards has found to be about double the visible radiation. As a source of ultra-violet light the quartz arc is used in paint and dye testing, photo-chemistry, the treatment of skin diseases, and in water sterilization.

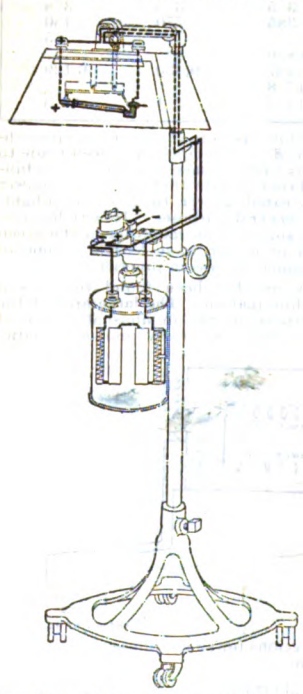


FIG. 36.—High-pressure mercury arc laboratory equipment.

126. Efficiency and life of quartz lamps. But little is published regarding the efficiency of the quartz lamp. Experience in this country shows, however, that early reports of very high efficiency which emanated from Europe, are not being realized in the forms of this lamp which have been developed. Twenty-one lumens per watt seems indicated as the initial efficiency of a 220-volt direct-current multiple lamp. About 17 lumens per watt is given by the 110-volt multiple direct-current lamp. In a series type a somewhat higher efficiency should be realized.

It has been found that in the course of 1,000 to 1,200 hr. the total radiation decreases about 40 per cent. while the ultra-violet component decreases somewhat more rapidly.* An effective burner life of 2,000 hr. is claimed by the manufacturers.

127. Moore tubes—nitrogen type. The Moore tube for general lighting purposes has been manufactured in lengths up to 200 ft. from glass tubes about 1.75 in. in diameter. This is filled with nitrogen which is replaced as required by an ingenious automatic valve which feeds the tubes at intervals of about one minute. The tube ends are enclosed in a sheet-metal box containing the tube electrodes, the gas tank, the gas valve, step-up transformer, etc. The efficiency of the nitrogen tube is of the order of 100 lumens per

*Bulletin S-330, Bureau of Standards, 1918.

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foot and the consumption is about 2.5 watts per candle-power. The power factor is about 75 per cent. The life of the tubes is very long.

128. Moore tubes—carbon-dioxide type. These tubes, which are usually shorter when employing carbon dioxide gas, yield light which very closely approximates average daylight. As the efficiency is quite low, the use of these tubes is practically confined to color-matching purposes. A modern simplified form with renewable tube consumes about 250 watts and produces intensities over a small area for color-matching up to 200 foot-candles.

129. Neon tubes. A six-meter tube operates at about 800 volts. The tubes are of about 1.75 in. in diameter. The electrodes are relatively large in order to reduce vaporization and avoid exhaustion of the gas. The tubes have a limited life, which, however, is said to be sufficient for commercial purposes. The life is longer for long tubes. The specific consumption is about 0.6 watt per candle. The light of the neon tube is distinctly lacking in blue radiations. In order to correct for this, a little mercury is employed in some of the tubes, with the neon. Such tubes are said to operate at about 1.0 watt per candle. When used in certain combination with tubes containing pure neon, a light which closely simulates daylight in appearance is obtained. A modified form of neon tube in which tubes of much smaller diameter are employed, is arranged to form script letters which serve for electric signs.

ACCESSORIES FOR ILLUMINANTS

GENERAL PRINCIPLES

130. The purpose commonly served by lighting accessories are as follows: (*a*) redirection of light; (*b*) concealment (partial or complete) of light source; (*c*) decoration. Local conditions peculiar to the installation determine choice and the weight to be given of these factors.

131. Reflectors. Since light sources commonly are located in the upper parts of rooms, and since the light is utilised chiefly in the lower part of the room, the most common form of auxiliary consists of an inverted bowl or a cone-shaped cover for the lamp, provided with an inner reflecting surface designed to redirect more or less of the light downward. Such reflectors are available in great variety; Par. **131** indicates the more common types classified with respect to various characteristics.

132. Redirection of light. A large proportion of the light emitted by a source may be intercepted and much of it may be redirected in the desired direction. The extent to which redirection is effected depends upon the following factors: (a) proportion of total flux intercepted by reflecting surface; (b) shape of reflecting surface; (c), properties of reflecting surface.

133. Light intercepted. Assume that opaque reflectors are made of various shapes and with a reflecting surface which absorbs 25 per cent. of incident light, whatever its direction. A reflector which is substantially flat intercepts, say, 40 per cent. of the total light flux. Another which covers the lamp fairly well intercepts say 80 per cent. of the flux. The flat reflector therefore occasions a loss of 10 per cent. of the total light flux, while the other results in a loss of 20 per cent. but is much more effective in redirecting a goodly proportion of the flux.

134. Reflector design. An ever-present obstacle in the design of reflectors for general illumination purposes is the relatively large area of the light source (lamp filament) as compared with the surface area of the reflector. If the light source were, in effect, a point, the reflector-design problem would be simplified. Dealing with a source of considerable area, the reflecting surface must be so designed as to redirect, in the desired direction, the light which it reflects, while allowing a minimum of flux to fall a second time upon a part of the reflector. Improper shape of reflecting surface, however favorable the reflection coefficient of the surface, may impair efficiency to a large extent by directing some of the flux back into the reflector instead of out and in the desired direction.

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135. Classification of reflectors

Principal class of service	Material	Reflecting surface	Usual shape	Distribution characteristic	Transmitted light	Per cent. reduction in total flux
Industrial	Enameled iron	Glossy	Flat inverted bowl or dome	Various	None	7 to 45
	Aluminum finish	Mat	Flat inverted bowl or dome	Medium and narrow	None	20 to 50
	Prismatic	Glossy	Inverted bowl or dome	Various	Some	8 to 25
	Mirrored glass	Glossy	Inverted bowl or dome	Various	None	15 to 35
	Mirrored glass	Glossy	Inverted bowl or dome	Various, including asymmetrical	None	12 to 40
	Prismatic glass	Glossy or mat	Inverted bowl or dome	Various, including asymmetrical	Some	8 to 30
Commercial	*White glass, light density	Glossy or mat	Bowl or dome	Medium and broad	Large	8 to 20
	White glass, medium density	Glossy or mat	Bowl or dome	Medium and broad	Some	8 to 20
	White glass, dense	Glossy or mat	Bowl or dome	Medium and broad	Little	10 to 30
Decorative-utility	Prismatic glass, etched	Mat	Various	Various	Various	10 to 30
	White glass, etched	Mat	Various	Various	Various	10 to 30
	Tinted glass	Glossy or mat	Various	Various	Little	20 to 80
Classification of shades						
Chiefly decorative	Etched clear glass	Glossy or mat	Various	Where shades are used primarily for ornamentation, the effect upon absorption or distribution of light is not usually given much consideration. Unless combined with a utility reflector, redirection of light is usually negligible and reduction in light flux is large.		
	Fabrics	Mat	Various			
	"Art" glass	Glossy or mat	Various			
	Metal	Glossy or mat	Various			
	Pottery	Glossy or mat	Various			
	Stone	Glossy or mat	Various			

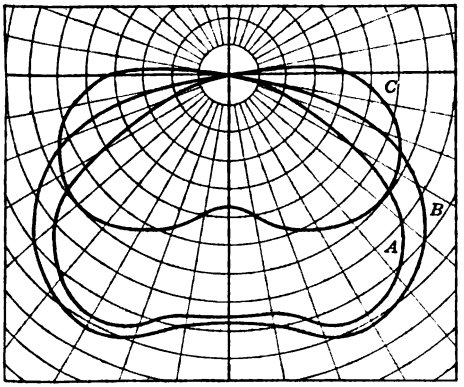
* Opal, phosphate, cased opal, milk, etc.

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136. Reflecting surfaces. A glossy or polished surface may reflect specularly or regularly, rendering an imperfect image of the source. Such surfaces are mirrors, polished aluminum, enamel and some glasses. Or the surface, if mat or depolished, may reflect the light irregularly or diffusely, as aluminumised steel, etched glass, etc. As a rule surfaces of the former class are the more efficient reflectors. Among surfaces employed for reflectors differences in absorption range from 25 to 75 per cent. Usually, the more efficient surfaces permit of more accurate control of light redirection.

137. Concealment of light sources. This has long been regarded as an essential of good illumination when bright light sources are employed. Exposed light sources occasion glare and decrease visual power. One of the serious difficulties encountered among the earlier designs of reflectors was the exposure of the light sources. During recent years this tendency has been overcome to a great extent, and the great majority of reflectors now produced conceal the source at least from ordinary view. Devices whose primary function is the concealment of the light source are often referred to as **shades.** This term is likewise applied to many lighting auxiliaries in which the decorative feature is dominant to the exclusion of efficiency in redirection of light. For most purposes a reflector may be of value in concealing the light source as well as in redirecting the light.

138. Distribution characteristics. In Fig. 37 are indicated the shapes and relative sizes of three reflectors, and the character of the distribution of light when used with a Mazda lamp.*









Percentage Light Flux			
Unit	*A*	*B*	*C*
Total Light from Lamp	100.0	100.0	100.0
Light Absorbed by Reflector	37.0	18.6	14.8
Light in Upper Hemisphere	0.0	0.0	6.4
Light in Lower Hemisphere	63.0	81.4	78.8
Light in 60 Deg. Zone	53.4	59.2	41.3

FIG. 37.—Light redirection by reflectors of various shapes.

"Reflector *A* resembles a parabola in shape with the lamp so placed as to obtain the greatest degree of concentration, and its angle of cut-off is considerably smaller than for *B*; consequently, one might expect this unit to produce by far the higher candle-power in a limited zone near the tip. It is seen, however, that from the standpoint of efficiency, even throughout

* Bulletin 20, National Electric Lamp Association.

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a narrow zone, nothing can be gained by the use of an enamel reflector o small diameter. The maximum intensities produced by units *A* and are practically identical, but the efficiency of *B* in the 50-deg. or wider zones considerably higher than the corresponding value for *A*.

"The distribution shown in curve *A* may be classed as intensive. B placing the lamp somewhat lower in the reflector, a more extensive distribu tion of light may be secured which will be preferable for most locations r quiring a general illumination. This form of curve, so far as distributio in the lower hemisphere is concerned, is practically ideal for industrial ligh ing purposes where the lamps are suspended at usual heights. The form this curve is desirable both because it tends toward a uniform illuminatio on the work, and because the lamp filaments are well screened. On th other hand, it must be remembered that the wider reflector, *B*, will practically all cases supply 10 or 15 per cent. more useful light than can obtained from a bowl-shaped unit in either the intensive or extensive positio Furthermore, the shadows resulting from the use of a light source of lar diameter, such as *B*, are less sharp than those from *A*."

139. Data on reflectors. In Par. **144** are given statistics of reflector used with 100-watt Mazda lamps, showing the light absorbed by the reflector some characteristics of the distribution obtained, and some physical data o the reflectors.

REFLECTORS FOR INDUSTRIAL LIGHTING

140. Porcelain-enameled reflectors.* "Any practical reflecting surfac absorbs a considerable percentage of the light incident upon it. Whe incandescent lamps were first used in industrial lighting, the efficiency o porcelain as a reflecting surface was recognized, and various translucen reflectors of this material came into extensive use. However, they wer not found entirely successful because they were lacking in mechanica strength; in many locations breakage resulted, causing the loss of th reflector and, which was more serious, often damaging material or injurin employees. It was largely for this reason that they were replaced by th metal reflectors of inferior efficiency but of greater ruggedness. Moder porcelain-enameled steel reflectors combine the good qualities of the glas and metal types. The surface absorbs about 35 per cent. of the incide light. As usually constructed in the bowl type these reflectors have a angle of cut-off of about 60° and in the dome type about 89°, the ligh output of the latter being of course higher than that of the bowl type. Th translucent neck, a recent modification of the dome reflectors, permits som light to reach the ceiling.

141. RLM standard dome. For general industrial purposes porcelain-enameled dome reflectors conforming to the Reflector and Lamp Manufacturers' Specifications are considered most desirable. The light output o such units must be at least 70 per cent.; large reflecting surfaces and a 17½° (72½° above nadir) cut off limit glare; and excessive downward concentratio of light is avoided.

142. Enamel-paint reflectors. "Metal reflectors with a surface o white enamel paint are available at prices materially lower than those asked for the porcelain-enameled products. However, owing to the relatively rapid depreciation of this surface and to the fact that these reflectors are seldom designed with proper regard for the efficient distribution of light, their use is likely to result in the waste of a considerable portion of the money annually expended for lighting. A loss of even 10 to 20 per cent. of the ligh in this manner will each year amount to several times the added cost for the most efficient equipment.

143. Aluminumized reflectors. "Aluminumized reflectors have approximately the same initial efficiency as the porcelain enameled, and allow a better control of the direction of light rays. Moreover, their cost is lower than that of porcelain-enameled equipment. On the other hand, reflectors of this class have heretofore failed to maintain their high initial efficiency in service. Their use is, therefore, to be recommended only where a better control of the light flux—for example, a concentrated distribution—is desired. An aluminumized surface has recently been developed which is superior to the older forms in maintaining efficiency.

* Bulletin 20, National Electric Lamp Association.

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144. Statistics of typical reflectors when used with 100-watt Mazda lamps*

(These statistics do not apply to any particular make of reflector but are the average obtained from reflectors of a number of different makes)

Type of reflector	Lamp	Total lumens	Light absorbed per cent.	Lumens distributed within zone		Diameter, in.	Weight, oz.
				0 to 60 deg.	0 to 90 deg.		
	Clear	999	.....	209	524	.....	.....
	Bowl frosted	943	.....	163	437	.....	.....
Porcelain-enameled flat dome	Clear	820	18	479	785	15.25	38.5
Porcelain-enameled flat dome	Bowl frosted	741	21	440	715	15.25	38.5
Porcelain-enameled radial fluted	Clear	913	9	339	688	18.0	40.0
Porcelain-enameled inverted bowl	Clear	600	40	510	600	8.75	22.0
Porcelain-enameled inverted bowl	Bowl frosted	506	56	441	506	8.75	22.0
Aluminum finished inverted bowl	Clear	570	43	490	570	8.50	11.5
Aluminum finished inverted bowl	Bowl frosted	525	44	460	525	8.50	11.5
White-glass inverted bowl	Clear	906	9	358	543	8.13	38.5
White-glass inverted bowl	Bowl frosted	842	10	315	480	8.13	38.5
White-glass flare	Clear	915	8	363	626	11.0	47.0
White-glass flare	Bowl frosted	880	6	326	584	11.0	47.0
Opal or opalescent bowl	Clear	806	19	430	600	7.8	21.5
Opal or opalescent bowl	Bowl frosted	748	21	377	478	7.8	21.5
Opal or opalescent flare	Clear	872	14	428	696	11.0	30.5
Opal or opalescent flare	Bowl frosted	795	16	392	629	11.0	30.5
Cased—opalescent inverted bowl	Clear	864	13	357	558	8.0	21.0
Cased—opalescent inverted bowl	Bowl frosted	795	15	338	490	8.0	21.0
Cased—opalescent flare	Clear	910	9	415	655	11.0	39.5
Cased—opalescent flare	Bowl frosted	841	11	356	581	11.0	39.5
Prismatic-glass inverted bowl	Clear	908	9	540	717	9.25	27.0
Prismatic-glass inverted bowl	Bowl frosted	855	9	485	651	9.25	27.0

* Stickney and Powell. Electrical World, September 6, 1913.

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thers, more appropriately classed as shades, are designed predominantly or decorative effect; these are of very little value where the illumination is o be utilized otherwise than for purposes of decoration. Among the latter re shades of "art" glass and metal or pottery, and of various fabrics. It would be futile to attempt to show data on such shades. On all reflectors ntended for industrial and commercial lighting including many which are ery decorative in appearance, definite engineering data are available. Typical information of this kind appears in Par. **150.**

150. Distribution of light in various zones about Mazda lamps and inverted bowl reflectors*

Type of reflector	Typical zonal distribution			
	0 to 60 deg., per cent.	0 to 90 deg., per cent.	0 to 180 deg., per cent.	Light absorbed, per cent.
Prismatic—focusing	50	68	87	13
Prismatic—intensive	44	65	87	13
Prismatic—focusing (satin finish)	40	60	87	13
Aluminized steel—intensive	51	58	58	42
Aluminized steel—extensive	52	61	61	39
Prismatic—intensive (satin finish)	37	57	87	13
Medium density—opal	40	54	82	18
Prismatic—extensive	40	62	86	14
Heavy density—opal (depolished)	41	59	72	28
Light density—opal	34	57	91	9
Prismatic—extensive (satin finish)	33	55	88	12
Bare lamp (for comparison)	16	47	100	

151. Depreciation due to dust. Certain information has been published showing the depreciation in reflecting efficiency due to collection of dust on lamps and reflectors in industrial service. Perhaps the most comprehensive data applicable to modern equipments of reflectors and Mazda lamps is that shown in Bulletin 20 of the National Lamp Works of the General

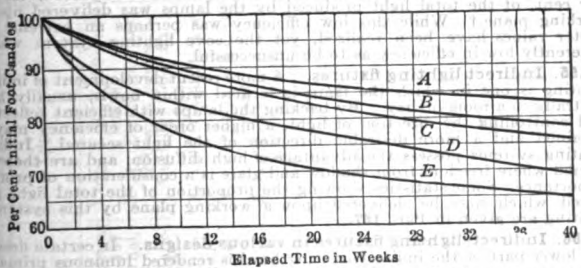


FIG. 38.—Reduction in light due to dust.

A. Dome enameled steel.
B. Bowl enameled steel.
C. Dense opal glass.
D. Prismatic glass.
E. Light density opal glass.

Electric Company published October, 1913. This is summarized in Fig. 38. The curves show decrease in illumination on the working plane.

152. Enclosing glassware. The sphere commends itself for many purposes of ornamentation and is therefore a popular form in design of lighting auxiliaries. It, with various modifications as to shape, forms an important class. Obviously, light absorptions run higher and light control

* Sweet. "The Choice of Reflector," Illg. Eng. Society, New York Section, Feb. 8, 1912.

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is less definite than is the case with open-mouth reflectors. In the matter of redirection of light, much may be accomplished in an ordinary glass sphere by varying the location of the light source within the sphere, but the tendency with such glassware is always to yield distribution characteristics which approach a circle. There are some forms of enclosing glassware, however, in which special attention has been given to this phase of the subject with very notable success in the redirection of light. Par. **153** gives some data upon enclosing glassware of various types.

153. Photometric data upon enclosing glassware employed with 1,000 lumen Mazda lamp*

Description	Lumens with glassware				Per cent. light absorbed by glassware
	0 to 60 deg.	0 to 90 deg.	90 to 180 deg.	Total	
10-in., 2-piece pressed-Alba ball	182	379	385	754	24
14-in., 2-piece pressed-Alba ball	190	384	335	719	28
12-in., 1-piece blown-Alba ball	223	469	395	864	14
12-in., blown-Alba acorn	243	476	347	822	18
12-in., cased Melilite ball	181	396	321	717	28
12-in., ground-glass ball	206	484	419	903	10
14-in., prismatic reflector bowl	412	589	180	769	23
12-in., prismatic reflector ball	455	618	103	721	28

INDIRECT LIGHTING

154. Cove lighting. Recognition some years ago of the need for concealing brilliant light sources from view led to systems of indirect lighting in which the light was thrown upon some reflecting surface which became a secondary source of illumination. One method consisted in locating the lamps within a cornice or cove concealed from view and illuminating the room via the ceiling. By this system, control of the light was largely lost, and efficiency of utilization was very low. In one case reported, only 15 per cent. of the total light produced by the lamps was delivered upon a working plane.† While this low efficiency was perhaps an extreme and better values have been realized, yet the cove lighting system was so inherently low in efficiency as to be unsuccessful.

155. Indirect lighting fixtures. A more recent development of indirect lighting is one in which the lamp is located within bowls, usually hung centrally in a room or bay. By backing the lamps with efficient reflectors, and controlling the direction of light, a higher order of efficiency may be obtained and a more desirable direction of the light secured. Indirect lighting systems possess the advantage of high diffusion, and are therefore valued where freedom from shadow and glare is a consideration of primary importance. Some statistics showing the proportion of the total light produced which may be delivered upon a working plane by this system of lighting are given in Par. **157.**

156. Indirect-lighting fixtures in various designs. In certain designs the lower part of the indirect-lighting bowl is rendered luminous primarily for purposes of decoration.‡ Sometimes small auxiliary lamps separately wired are employed in this part of the fixture.

Indirect lighting fixtures mounted upon pedestals have been employed with pleasing results in interiors which lend themselves to such treatment.§

* "Characteristics of Enclosing Glassware." Lansingh, *Transactions* Illuminating Engineering Society, 1913, p. 447.

† "The Elements of Inefficiency in Diffused Lighting Systems." Millar. *Transactions* Illuminating Engineering Society, 1907, p. 583.

‡ Stair and Hoeveler, *Transactions* Illuminating Engineering Society, 1916, p. 794.

§ Curtis and Stair, *Transactions* Illuminating Engineering Society, 1920.

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157. Data on indirect-lighting installations

Source of data	Type of unit	Area illuminated	Ceiling	Walls	Per cent. total flux falling on working plane
Butler & Hoeveler, Lighting Journal, Aug., 1913, p. 197	X-ray E-200, 100-watt lamps	Office 150 by 170 ft	Light cream	Dark cream	39.0
Wheeler, Lighting Journal, Sept., 1913, p. 218	X-ray E-255, 100- and 200-watt lamps	School auditorium 5,936 sq. ft.	Light cream	Upper ½ light cream Lower ½ fumed oak	30.5
Woodhead, Lighting Journal, Oct., 1913, p. 242	Alexalite, 500-watt lamps	Display room 201.5 by 58.5 ft.	.....	Dark ivory	24.6
McDermott, Lighting Journal, Oct., 1913, p. 245	X-ray 100-watt lamps	Hospital ward 20 by 15 ft.	White	Yellow buff	24.8
Wheeler, Lighting Journal, Nov., 1913, p. 269	X-ray E-100, 60-watt lamps	Hospital ward 20 by 32 ft.	Flat white	Flat white	30.5
Wheeler, Lighting Journal, Nov., 1913, p. 269	X-ray E-200, 100- and 60-watt lamps	Hospital ward 33.5 by 74 ft.	Flat white	Flat white	27.7
Wheeler, Lighting Journal, Nov., 1913, p. 269	X-ray E-60, 40-watt lamps	Private hospital ward 14.5 by 16.5 ft.	Light yellow	Light buff	31.3
Wheeler, Lighting Journal, Nov., 1913, p. 269	X-ray E-60, 40-watt lamps	Nurses duty room 10 by 16 ft.	White	Cream	29.8
Wheeler, Lighting Journal, Nov., 1913, p. 269	X-ray E-200, 150-watt lamps	Operating room 20 by 24 ft.	Flat white	Flat white	28.0
Wheeler, Trans. I. E. S., 1912, p. 168	X-ray 100- and 250-watt lamps	Church auditorium	Ivory white	Cream	26.3
Cravath, Trans. I. E. S., 1909, p. 292	X-ray 100-watt lamps	Small room (parlor) 15 by 15 ft. 2 in.	Light cream	Dark green	28.0
Cravath, Trans. I. E. S., 1909, p. 292	X-ray 100-watt lamps	Small room (bedroom) 12 ft. 8 in. by 12 ft. 9 in.	Light cream	Light in tone	36.4
National X-ray data book	X-ray	.....	Light	Light	30.0
Handbook N. E. L. A.	.....	.....	Light	Light	33.0
Sweet, I. E. S., 1912	Special	Small room	Light	Light	29.0
Sweet, I. E. S., 1912	Special	Small room	Light	Medium	19.0
Sweet, I. E. S., 1912	Special	Small room	Light	Dark	10.0

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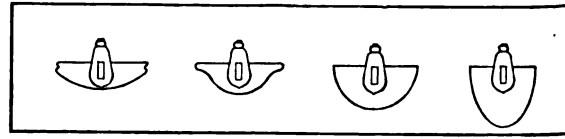
SEMI-INDIRECT LIGHTING UNITS

158. Translucent bowls. A development of the past few years consists in the use of glass bowls enclosing the light source and reflecting most of the light to the ceiling, as in the indirect lighting system, while transmitting in various proportions enough light to give an appreciable direct component. Some data upon bowls of this type, of one manufacture, are presented in Par. **160**. Referring to the data in this table it will be seen that the authors have made a study of the influence of contour of bowl upon the distribution of light, and likewise of the influence of optical density of glassware. Their conclusions from these figures and others given in the paper, follow in Par. **159**. Data on semi-indirect installations appear in Par. **163**.

159. Effect of change of light source and bowl contour. "The distribution of light is materially affected by changes in the position of the lamps within the bowl; changing from a single lamp to a closely clustered group of two or three lamps does not introduce large variations in the distribution characteristics, although the single lamp results in a somewhat wider distribution above the horizontal. The ratio of light above the horizontal to that below the horizontal in the four types of glass of the contour 3, chosen for this purpose, vary from 1.26 for the least dense (etched glass) to 6.4 for the most dense (Calla); and the effect of change in the contour of the bowls is that with the shallower bowls the distribution both above and below the horizontal is not so wide, more light being centred near the bowls while with the deeper bowls there is, of course, a larger ratio horizontal."

160. Photometric data of semi-indirect glass bowls employed with one Mazda lamp*

Description of glassware	Contour, see Fig. 39	Per cent. of total light from lamp which is distributed within stated zones†			
		180 deg. to 120 deg.	180 deg. to 90 deg.	90 deg. to 0 deg.	Total
Etched crystal glass with new cut design....	3	22	47	37	84
Druid.....	3	27	54	30	84
Veluria.....	1	36	60	25	85
	2	36	58	24	82
	3	30	57	24	82
	4	28	60	24	84
Calla.....	1	44	68	11	79
	2	46	71	11	82
	3	41	68	11	79



1 2 3 4

FIG. 39.—Contours referred to in Par. **160**.

161. Reflectors in railway coaches. Some information upon the distribution of light in a typical railway day coach has been made available by the Committee on Illumination of the Association of Railway Electrical

* "A Photometric Analysis of Diffusing Bowls with Varying Indirect Component." Rowe and Magdsick, *Trans.* Illg. Eng. Soc., 1914.
† 180 deg. is the Zenith; 0 deg. is the Nadir.

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162. Data on semi-indirect lighting installations

Source of data	Type of unit	Area illuminated	Ceiling	Walls	Per cent. total flux falling on working plane	In terms of comparable direct lighting system, Per cent.
Univ. of Mich., E. E. Dept., Elec. World, Mar. 28, 1914, p. 715.	Alba Hem. 3 60-watt lamps	Display room 60 by 37 ft.	White	White	30.8	.....
Univ. of Mich., E. E. Dept., Elec. World, Mar. 28, 1914, p. 715	Alba Hem. 3 60-watt lamps	Office 60 by 48 ft.	White	White	31.2	.....
Henninger, I. E. S. Trans., 1912, p. 248	Inverted prismatic	Room 18 ft. 10 in. by 23 ft.	Factory white	Natural pine	.....	50.6
Cravath, I.E. S. Trans., 1912, p. 402	Bowl-shaped opal glass (inverted)	Small room 12 by 16 ft. 6 in.	Light cream	Light green	37.6	71.0
Sweet, I. E. S. Meeting, Feb. 8, 1912	.....	.....	Light	.....	25.0	55.0
Sweet, I. E. S. Meeting, Feb. 8, 1912	.....	.....	Medium	.....	18.0	42.0
Sweet, I. E. S. Meeting, Feb. 8, 1912	.....	.....	Dark	.....	11.0	28.0
N. E. L. A. Handbook for Railway Elec. Engineers	.....	.....	Light	.....	35.0	65.0
Aldrich and Malia, I. E. S. Trans., 1914, p. 111	Inverted opal reflector 100-watt lamps	Large room	Light cream	Light buff and green	50.7	92.2
Edwards and Harrison, I. E. S. Trans., 1914, p. 171	Inverted opal reflector and hemisphere	Small room 14 ft. 6 in. by 17 ft. 9 in.	Light	Green-gray	21.0	62.0

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Daylight may be simulated in a manner satisfactory to the eye by combining illuminants of a variety of hues, as tungsten filament and mercury vapor lamps. The pronounced line spectrum of the latter, however, renders such light unsuitable for color matching purposes.

Incandescent illuminants in general produce light which is redder than natural light. Color filters which absorb selectively the longer wave lengths may be employed with such illuminants to obtain the equivalent of any quality of daylight. Most artificial daylight units are of this kind. The gas-filled tungsten lamp is usually the source and bluish glass color filters are used to suppress the red end of the spectrum.

One combination is a "noon sunlight equivalent." About 50 per cent. of the light from a Mazda C lamp is absorbed. The filtered remainder is a satisfactory substitute for sunlight. Another combination is a "north skylight equivalent." About 80 per cent. of the light from a Mazda C lamp is absorbed in this unit. On this account it is employed only to illuminate small areas for the most exacting color matching purposes.

A blue bulb "daylight" lamp (Mazda C-2) offers a popular compromise between daylight and artificial light. As this absorbs only about one-third of the light of the Mazda "C" lamp, its use becomes practicable for larger areas such as show-windows. It is customary when using these lamps to choose the next size larger than the size of clear bulb lamps which would be employed.

When light of a particular hue is required the most significant efficiency is the relative efficiency as compared with other units, if any, which produce light of the same hue. It may be a real economy to make a large expenditure to obtain only a little light of the required quality.

ACCESSORIES FOR SPECIAL PURPOSES

165. Show-window lighting. For show-window lighting and certain other purposes an asymmetrical distribution of light is usually required. Example of reflector designed for such a purpose is shown in Fig. 40.

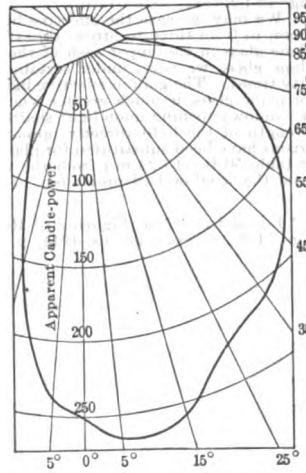


FIG. 40.—Asymmetrical distribution, adapted to show-window lighting.

166. Street lighting. Various auxiliaries for redirecting part of the light produced by street illuminants have been developed. Some of the most effective in this respect are to be found among the newer designs of auxiliaries for Mazda type *C* (gas-filled) series lamps. Illustration of this is given in Fig. 41. In some street illuminants, as the magnetite and metallic-flame arc lamps, a reflector is built in the lamp casing. In others, the diffusing globes with which the lamps are equipped are so shaped as to modify the distribution characteristic materially. These are inconspicuous methods of accomplishing a measure of light redirection which usually is less marked than that accomplished by the use of external reflectors.

167. Glass plates. Translucent glass plates consisting either of frosted glass, opal glass, so-called art glass, ribbed glass or prismatic glass are largely employed as skylights and as diffusing screens for artificial lighting. Some data upon the transmission coefficient of such glasses are given in Par. **169.**

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168. Glass for redirecting daylight. Ribbed and prismatic glass is used to a large extent in industrial lighting for directing into large rooms a

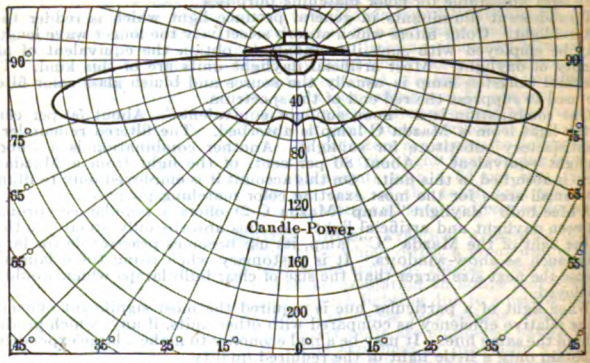


FIG. 41.—Distribution of light in vertical plane about lamp equipped with prismatic refractor for street lighting.

greater amount of skylight than would otherwise be available. Some tests by Professor Norton are commented upon in the Johns Hopkins University Illuminating Engineering Society Lecture Course on Illuminating Engineering* as follows:

"We may increase the effective light in a room 30 ft. (9.14 m.) deep or more, to from three to fifteen times by using factory-ribbed glass instead of plane glass in the upper sash of the window. By using prisms, instead of plane glass, we may, under certain conditions, increase the effective light fifty times. The gain in effective light on substituting ribbed glass or prisms for plane glass, is much greater when the sky angle is small, as in the case of windows opening upon light shafts or narrow alleys. The increase in the strength of the light directly opposite a window in which ribbed glass or prisms have been substituted for plane glass is at time such as to light a desk or table 50 ft. (15.24 m.) from the window better than one 20 ft. (6.1 m.) from the window had previously been lighted."

* Edwards. "The Lighting of Rooms through Translucent Glass Ceilings," I. E. S. *Transactions*, 1914, p. 1014.

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169. Light from Mazda lamps transmitted through glass plates‡

No.	Mounting height to spacing distance-ratio necessary for elimination of spotting	Transmission efficiency per cent.	Character of glass	Trade name
1	19	45	Light opal	Alabaster Cathedral
2	†	46	Yellow and iridescent.	Iridescent No. 6
3	3	39	Opal	Alabaster Illuminal
4	4	65	Clear	Cristallia Illuminal
5	2	35	Very light opal	Alabaster Moss
6 & 6a	11	63	Clear	Deflex No. 1
7	8	44	Yellow	Deflex No. 1½
8	5	43	Opal light	Opalescent No. 139, G.L.L.
9	2	54	Clear	Cristallia No. 40
10	2	33	Opal	Pattern No. 40, Opal No. 65
11	3	50	Clear	Pattern No. 41
12	2	40	Yellow	Pattern No. 41, Amber
13	3	29	Opal	Pattern No. 41, Opal No. 65
14	3	36	Clear	Cristallia No. 42
15	3	37	Opal	Pattern No. 42, Opal No. 65
16	2	22	Violet	Pattern No. 42, Violet
17	3	41	Clear	Cristallia No. 43
18	3	39	Yellow	Pattern No. 43, Yellow No. 21.
19	3	30	Opal	Pattern No. 43, Opal No. 65
20	2	34	Clear	Cristallia No. 45
21	4	28	Opal	Pattern No. 45, Opal No. 65
22	3	18	Dark yellow	Pattern No. 45, Yellow 3X
23	4	41	Clear	Cristallia No. 46
24	4	31	Opal	Pattern No. 46, Opal No. 65
25	4	66	Clear	Multiflora Crystal
26	4	46	Opal light	Multiflora Opal No. 65
27	3	37	Yellow	Multiflora Yellow
28	3	35	Opal	Multiflora No. 68
29	*	36	Opal	Opal, light
30	*	35	Opal	Opal, medium
31	2	28	Opal	Opal, dark
32	*	69	Clear	Deflex No. 6
33	*	45	Clear	Pattern No. 6, Honey Comb
34	3	36	Clear	Pattern No. 7, Bee Hive
35	5	35	Opal	Pattern No. 44, Opal No. 65
36	15	57	Clear	Ripple No. 3

170. Headlights. Space does not permit specific treatment of light projection. Searchlights, locomotive headlights,‡ automobile headlights§ and moving-picture projectors‖ offer distinctive problems.

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* Marks. "Principles and Design of Interior Illumination," Vol. II, p. 660.

† Impossible to eliminate spotting with any reasonable ratio.

‡ Report of Committee on Locomotive Headlights, *Railway Electrical Engineer*, October, 1913.

§ McMurtry, Headlamp Design and its Effect upon Glare Reduction, *Bulletin Society of Automotive Engineers*, April, 1917.

‖ Illuminating Engineering Practice, 1916, I. E. S., U. P., p. 213.

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ILLUMINATION CALCULATIONS

GENERAL CONSIDERATIONS

171. Light flux. According to approved concept, light is regarded as luminous flux.* The output of a lamp is its **total luminous flux.** The brightness of a diffusely reflecting or transmitting surface is proportional to its **specific luminous flux.** The intensity of illumination received on any surface is the **flux density.** Thus luminous flux is analogous to magnetic and electrostatic flux. Comprehension of light flux is facilitated by considering a point source to be located at the centre of an imaginary non-reflecting sphere. The total luminous flux produced by a source of 1 c-p. radiated uniformly, is divided by the number of unit solid angles or steradians in the sphere in order to arrive at the unit of luminous flux which is the lumen "equal to the flux emitted in a unit solid angle (steradian) by a point source of 1 c-p."

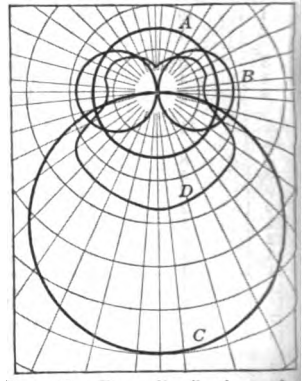


FIG. 42.—Four distributions of a given flux.

172. Distribution of light. In practice, light is rarely radiated uniformly, and it is therefore necessary to consider the flux to be distributed in a great variety of ways. The determination of light distribution characteristics of sources, is a regular part of illuminating engineering practice, and most calculations performed involve this distribution characteristic. In Fig. 42 are illustrated four different distributions of a given luminous flux. The curves show a section of revolution. The circle (curve *A*) indicates uniform distribution from a punctiform source; curve *B* shows distribution from a theoretical line source, distributing no light at the poles. Curve *C* shows the distribution from a uniformly radiating circular disc, and curve *D* shows a light-distribution characteristic typical of a certain class of reflectors.

COMPUTATION OF TOTAL FLUX, OR MEAN SPHERICAL CANDLE-POWER

173. Zonal areas. In Fig. 43, curve *D* from Fig. 42 is reproduced. The polar diagram at the left shows the flux density or intensity in any direction in the vertical plane, considered. Referring to the representation of a sphere on the right, it will be noted that the total area of a zone of a given altitude at the equator is much greater than the total area of a similar zone near the pole. The flux density, or intensity, of the light distributed throughout each zone, is indicated in the distribution curve to the left. The area of each zone must be multiplied by the mean flux density, in order to obtain the total flux distributed throughout the zone.

174. Rousseau's method. Rousseau's method of determining the total flux distributed through the zone, is the basis of most such computations. This method is indicated in the middle of the diagram. The zone latitudes, as represented upon the sphere, are projected upon a rectilinear diagram, upon which the zone widths then become proportional to the areas of the zone upon the sphere. The curve of light distribution, when plotted upon this diagram in the manner indicated, will comprehend an area proportional to the total

* Sharp. "The Concepts and Terminology of Illuminating Engineering." Trans. Illg. Eng. Society, 1907, p. 414.

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luminous flux. The mean altitude of such a curve is proportional to the mean flux density (which is to say, the mean spherical candle-power). Furthermore, the area comprehended in any zone by the curve, is proportional to the zonal flux, and the mean altitude of the curve within that zone is proportional to the mean flux density or candle-power within that zone. The area comprehended by the curve may be obtained by the use of a planimeter, or by averaging altitudes at short equal intervals. It is apparent, therefore

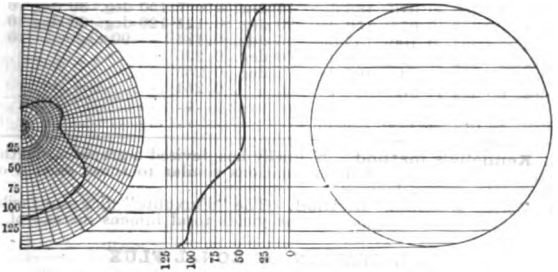


FIG. 43.—Relation between flux and intensity.

that flux values may be obtained from the light distribution curve without the preparation of a Rousseau diagram, by averaging the flux density or candle-power values at angular intervals corresponding to equal intervals on the Rousseau diagram. Such angles are given in Par. 175. Macbeth has prepared polar coordinate paper on which such angular intervals are indicated.

175. Angles from vertical axis at which values may be taken from a light distribution curve and averaged to obtain mean flux density or mean candle-power in each hemisphere

Ten points	Six points
18 deg. 63 deg.	24 deg.
32 deg. 70 deg.	41 deg.
41 deg. 75 deg.	54 deg.
49 deg. 81 deg.	65 deg.
57 deg. 87 deg.	75 deg.
	85 deg.

176. Mean zonal-candle-power constants. When photometric values of light distribution are available but have not been plotted to form a light distribution diagram, the flux computation may be carried out by the application of the constants in Par. 177, which are proportional to the areas of the several zones of which the test angles are representative. In using these constants, find the product of each candle-power value and the constant for its angle. Divide the sum of all such products by two to determine mean spherical candle-power. Multiply the mean spherical candle-power by 12.57 to obtain total lumens. To determine mean hemispherical candle-power employ same constants except for the 90-deg. value where the given constant should be divided by two. In this case, do not divide the sum of the products by two.

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177. Constants for computation of mean spherical candle-power or total flux from light-distribution data

10 deg. zones		15 deg. zones		30 deg. zones	
Angles from vertical axis	K	Angles from vertical axis	K	Angles from vertical axis	K
175 deg. 5 deg.	0.016	180 deg. 0 deg.	0.009	180 deg. 0 deg.	0.034
165 deg. 15 deg.	0.046	165 deg. 15 deg.	0.067	150 deg. 30 deg.	0.259
155 deg. 25 deg.	0.074	150 deg. 30 deg.	0.131	120 deg. 60 deg.	0.448
145 deg. 35 deg.	0.100	135 deg. 45 deg.	0.184	90 deg.	0.518
135 deg. 45 deg.	0.124	120 deg. 60 deg.	0.226	.....	.....
125 deg. 55 deg.	0.142	105 deg. 75 deg.	0.253	.....	.....
115 deg. 65 deg.	0.158	90 deg.	0.261	.....	.....
105 deg. 75 deg.	0.168	.....	.....	.....	.....
95 deg. 85 deg.	0.174	.....	.....	.....	.....

178. Kennelly's method. Kennelly has devised a graphical method of rectilinear construction for determinations similar to those carried on by means of a Rousseau diagram.*

179. White-Wohlauer method. The "Fluxolite" diagram facilitates the same kind of computations, but yields total lumens instead of mean candle-power.†

COMPUTATION OF ZONAL FLUX

180. Zonal flux. This does not differ from calculation of total flux. In fact most determinations of total flux or of flux in one hemisphere are merely additions of zonal-flux values. The Rousseau, Kennelly and White Wohlauer methods yield zonal flux readily. Constants for use in determining mean zonal candle-power directly from angular candle-power values are given in Par. **181** for certain zones. Multiply the sum by 2π (6.28) times the difference between cosines of limiting angles to obtain corresponding lumens.

181. Constants for use with candle-power values to yield approximate mean zonal candle-power

Angle from vertical axis at which c-p. is known	Constants 75-deg. zone	Constants 60-deg. zone	Constants 45-deg. zone	Constants 30-deg. zone
10-deg. intervals				
70 deg.	0.221	.....	.....	.....
60 deg.	0.204	0.147	.....	.....
50 deg.	0.180	0.267	.....	.....
40 deg.	0.151	0.224	0.383	.....
30 deg.	0.117	0.174	0.297	0.301
20 deg.	0.080	0.119	0.203	0.445
10 deg.	0.041	0.060	0.104	0.226
0 deg.	0.005	0.008	0.013	0.029
15-deg. intervals				
75 deg.	0.170	.....	.....	.....
60 deg.	0.304	0.219	.....	.....
45 deg.	0.249	0.369	0.295	.....
30 deg.	0.176	0.261	0.446	0.432
15 deg.	0.090	0.135	0.230	0.504
0 deg.	0.012	0.017	0.029	0.064

* Kennelly. *Electrical World*, March 28, 1908.
† Wohlauer. *Illuminating Engineer*, Vol. III, p. 655.

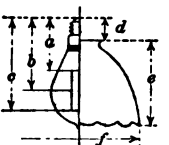
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182. Zonal constants approximate only. In using zonal constants it must be remembered that the candle-power is assumed to represent the mean intensity throughout the zone. In many cases this assumption is not strictly justifiable. Hence this is only an approximation method.

183. Typical zonal values. Fig. 44 is a reproduction of a typical test-data sheet bearing on the right a graph of the light distribution in a mean vertical plane about a source, and on the left corresponding zonal-flux values.

Lamp - 250-Watt Bowl-Frosted Metallized Filament
Holder - Form "A"
Photometric Distance - 10 Feet
Conditions - Lamp and Auxiliary Rotated

Dimensions of Lamp and Auxiliary



a ..4½ in.
b ..6½ "
c ..8 "
d ..1⅝ "
e ..8 "
f ..12 "

Mid-zone Angles	Distribution Mean Vertical App. Candlepower		Zonal Lumens	
	Lamp Alone	Lamp with Aux.	Lamp Alone	Lamp with Aux.
180° Zenith	28.9	23		
175°	31.2	26	3	2
165°	42.8	31	12	9
155°	55	35	25	16
145°	69	39.1	43	25
135°	77	45	60	35
125°	86	49	77	44
115°	90	50	89	50
105°	91	51	96	53
95°	87	46.5	95	51
90° Horiz.	86	46		
85°	85	47.5	98	52
75°	79	53	84	56
65°	71	71	71	71
55°	58.5	93.5	52	84
45°	52	99	40	77
35°	45.6	102	29	64
25°	42.7	105	20	49
15°	40.7	107	12	30
5°	39.6	112	4	11
0° Nadir	39.1	113		
Spherical Values	72.0	62.0	905	779

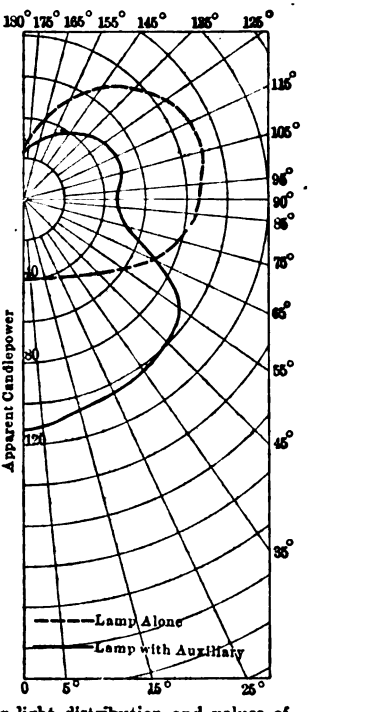


FIG. 44.—Photometric test sheet showing light distribution and values of intensity and flux.

184. Spherical reduction factor. In rating some types of illuminants, notably incandescent lamps, it has unfortunately been customary to adopt as a basis the mean flux density or candle-power in a horisontal plane through the source. Whether rated in this way or by the candle-power in some other direction or plane, it is always desirable to reduce the values to total light flux for some purposes. Hence reduction factors are commonly given with some illuminants, and the term, "spherical reduction factor," has come to be applied especially to the ratio between mean spherical candle-power and mean horisontal candle-power of incandescent electric lamps. (See Par. 30.)

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CALCULATIONS OF ILLUMINATION INTENSITY

185. Classification of methods. Assuming that light distribution data, such as those presented in Fig. 44 are available, it becomes possible to compute the illumination produced upon any given plane by the light source in any given location. For the sake of simplicity it will be considered that the light source, whose distribution is indicated in the diagram, is mounted over the centre of a horizontal plane which is to be illuminated. For such computations there are three customary methods. The flux of light delivered upon the horizontal plane will be the sum of that directed toward the plane from the source and that reflected to the plane from ceiling, walls, etc.

186. Flux method (direct light). For many purposes an approximate calculation of the flux delivered upon the plane of reference is adequate. In such cases it may serve to determine the approximate square feet of the plane to be illuminated and to estimate the total flux which will reach such plane. For example, assume that a certain room has a floor area 12 ft. 7 in. by 12 ft. 2 in., and that it is desired to estimate the light flux delivered upon a horizontal plane 36 in. above the floor from a light source located over the centre of the area, and 6 ft. 4 in. above the plane of reference.* Roughly, the flux delivered within an angle of 45 deg. above the horizontal will fall upon this plane. Applying zonal constants (Par. 181) to the candle-power values in Fig. 44, we have either or both of the following:

Angle	Constant c-p.	Angle	Constant c-p.
40	$0.383 \times 100 = 38.3$	45	$0.295 \times 99 = 29.2$
30	$0.297 \times 102 = 30.3$	30	$0.446 \times 102 = 45.4$
20	$0.203 \times 105 = 21.3$	15	$0.230 \times 107 = 24.6$
10	$0.104 \times 110 = 11.4$	0	$0.029 \times 113 = 3.3$
0	$0.013 \times 113 = 1.51$	.....	.....
Mean zonal c-p.....102.81		Mean zonal c-p.....102.5	

With a mean candle-power of 103 distributed throughout a zone extending from the nadir to 45 deg., the flux in lumens is found by multiplying 103 by the number of unit solid angles in the 45. deg. zone or $103 \times 2\pi (\cos \theta_0 - \cos \theta_{45}) = 190$ lumens.

187. Flux method (indirect light). Referring to report of test* of the installation described it will be seen that the lumens directed to the plane of reference by the lighting unit are 191 in number, with which value the above determination is in accord. The light source produces 779 lumens. As 191 lumens reach the plane of reference (779 − 191 =) 588 are incident upon ceiling and walls, where they are partly absorbed and partly reflected either toward the plane of reference or elsewhere. The greatest uncertainty in estimating total flux on a plane is arriving at the amount of such indirect light. The test* shows that 189 lumens or (189/588 =) 32 per cent. of this flux, which the lighting unit directed elsewhere, ultimately reached the plane of reference, thus equalling the light directed toward the plane by the lighting unit. In this case the room was small and the reflection from ceiling and walls was more effective than usual. If instead of a room the area is a bay in a larger room, the light, which here falls upon the walls, will add to the illumination of adjoining bays, and the bay under consideration will profit likewise from adjoining bays. In any installation this indirect light must be estimated taking into consideration the flux directed elsewhere than upon the plane of reference and the reflecting qualities and location of the reflecting surfaces. Some data on this subject are given in Par. 167.

COEFFICIENTS OF UTILIZATION

188. Definition. Where the illumination of such a plane is the principal purpose of the lighting installation, the ratio of flux delivered upon the plane to total flux produced by the illuminant is sometimes called the "coefficient of utilization." In this case, assuming that the reflector used with the

* Actual conditions described by Sharp and Millar, "Illumination Tests." *Trans.* Illg. Eng. Soc., 1910, p. 391.

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illuminant absorbs 20 per cent. of the total flux produced, there will be a coefficient of utilisation of 376/(779/0.8) = 0.39 per cent.

189. The coefficients of utilisation in the following table are representative of square rooms equipped with a sufficient number of lighting units and so placed as to produce reasonably uniform illumination. In each case the upper figure applies to an extended area, namely, one in which the horisontal dimension is at least five times the distance from floor to ceiling. The lower figure applies to a confined area, one in which the floor dimension is but five-fourths of the ceiling height. The utilisation factor for a rectangular room is approximately the average of the factors for two square rooms of the large and small floor dimension respectively.

190. Coefficients of utilisation*

Ceiling, reflection factor	Light, 70 per cent.			Medium, 50 per cent.	
Walls, reflection factor	Light, 50 per cent.	Medium, 35 per cent.	Dark, 20 per cent.	Medium, 35 per cent.	Dark, 20 per cent.
Lighting equipment:					
Direct, prismatic	65	61	59	58	56
	40	37	36	36	35
Direct, light opal	57	53	50	48	46
	33	28	27	26	24
Direct, dense opal	61	58	57	56	53
	40	35	34	34	32
Direct, steel bowl, enamel or aluminum.	57	55	54	54	53
	39	36	35	35	34
Direct, steel dome, enamel	70	67	65	67	65
	46	42	39	42	39
Totally indirect, mirrored.	40	38	36	27	26
	24	21	20	15	14
Semi-indirect, light opal	47	45	43	39	35
	30	25	24	22	20
Semi-indirect, dense opal	43	41	40	31	30
	27	25	22	18	17
Totally enclosing	46	42	40	38	35
Light opal	25	10	18	18	15

191. Coefficients of utilisation in small room. Lansingh† has made available data for a room 12 by 14 ft. having a 10-ft. 3-in. ceiling. The reflection factor of ceiling was 52 per cent. With various wall and floor reflection factors the following coefficients of utilisation among others were obtained with lighting units as described:

Unit	Output, per cent.	Flux ratio: upper hemi. to lower hemi.	With reflection factor of floor 17 per cent.: Coefficients of utilisation	
			11 per cent. walls	31 per cent. walls
Indirect	71	70.9 / 0.14	15	17
Semi-indirect	72	56.6 / 15.2	28	31
Direct	75	27.5 / 47.6	28	29

* Illg. Eng. Practice, I. E. S., U. P., 1916, p. 52.
† *Transactions* Illuminating Engineering Society, 1920.

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192. Further data on coefficients of utilization. Messrs. Harrison and Anderson* have made available extensive data based upon experiments in a test room and adapted to practical requirements. Summary taken from this paper is presented in Par. **195** and **196**. These data show the extent to which increasing heights of ceiling and of lamp mounting increase the coefficient of utilization with all forms of lighting units. They show the increasing importance of high reflection factor of ceiling as more of the light flux is directed toward the ceiling, and they show the relatively less important effect of walls in influencing the coefficient of utilization, this last of course becoming more important when the rooms are very small. The data are for new and clean equipments. (For depreciation data see Par. **151**.)

193. The flux method. From the accompanying data it is possible to form a reasonably accurate estimate of the influence of ceiling and walls upon coefficients of utilization. Rough estimates of the flux ultimately reaching a plane of reference may be made with fair accuracy after a little experience.

In many cases it is desirable to invert the order of computation, and beginning with the desired illumination intensity upon a given plane, arrive at an estimate of the total light flux to be produced. Taking the case assumed in Par. **186** and assuming that an average illumination intensity of 5 foot-candles or 5 lumens per square foot is required, we may carry out such a computation in simple manner. The area of the room is 153 sq. ft., which multiplied by 5 foot-candles gives 765 lumens to be applied upon the plane of reference. It may be assumed that this can be accomplished by using lighting equipment which, while directing most of the light toward the plane, will still transmit sufficient to illuminate the ceiling and walls acceptably. With such equipments it is reasonable to expect that 50 per cent. of the light may be delivered upon the plane of reference. Therefore twice the applied lumens should be generated, or 1,530 lumens. This will be produced by a 150-watt Mazda "C" lamp of about 2,050 lumens, thus leaving a margin of about 25 per cent. for depreciation due to dust and falling-off of the light output of the lamp during life.

194. Absorption of light method. An alternative method of computing light flux for an illumination installation is the "absorption of light" method.† This is based upon the fundamental consideration that all of the light within a room being absorbed, the illuminants must produce the sum of the light flux absorbed by the various surfaces. That is to say, the average incident flux upon each surface multiplied by the coefficient of light absorption characteristic of that surface and by the area of the surface will yield the total flux absorbed by that surface, and the sum of the flux absorbed by all exposed surfaces within a room must aggregate the total flux to be produced by the lighting unit. (In such case of course, the absorption of light involved in the use of an auxiliary must be added to this aggregate to ascertain the total amount of light to be produced by the illuminant proper.) Referring to the room already mentioned‡ we find the data necessary to verify this method. These are summarized below.

Absorption of light in a given room

Surface	Lumens		
	Incident from all directions	Coefficient of absorption	Absorbed
Ceiling	280	0.14	39
Walls	672	0.57	382
36-in. horizontal plane	376	1.00	376
Total			797

* Harrison and Anderson. *Trans.* Illg. Eng. Soc., 1920.

† McAllister. "The Absorption of Light Method of Calculating Illumination." *Electrical World*, November 21, 1908.

‡ Actual condition described by Sharp and Millar "Illumination Tests," *Trans.* Illg. Eng. Soc., 1910.

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195. Coefficients of utilization

The proportion of the total light from the lamps reaching the plane of the work is the coefficient of utilization of an installation. For a given reflector equipment the coefficient is dependent upon the color of the ceiling and walls, and upon the "Room Ratio," which is the relative width of the room compared with the height of the light sources above the level of the work. This table of coefficients applies to installations having sufficient lighting units symmetrically arranged to produce reasonably uniform illumination.

Square rooms.—To find coefficient of utilization,

1. Determine room ratio.

For **direct** installations (first 16 units of table),

$$\text{Room ratio} = \frac{\text{width of room}}{2 \times \text{height from plane of work to } \textit{lamps}}$$

For **indirect** and **semi-indirect** installations, (last 4 units of table),

$$\text{Room ratio} = \frac{\text{width of room}}{1\tfrac{1}{2} \times \text{height from plane of work to } \textit{ceiling}}$$

2. Find coefficient in proper column of ceiling and wall colors opposite this room ratio value.

Rectangular rooms. Find the coefficient as above for a square room of the narrow dimension and add one-third of the difference between this value and the coefficient for a square room of the long dimension.

Color (Reflecting Value) of Ceiling / Walls			Light (70%)			Medium (50%)		Dark (30%)
			Light (50%)	Medium (30%)	Dark (20%)	Medium (30%)	Dark (20%)	Dark (30%)
Reflector Type	Light Output	Room Ratio	Coefficients of Utilization					
Clear Lamp		1	.46	.43	.41	.42	.40	.40
		1½	.54	.51	.48	.50	.47	.47
		2	.60	.57	.54	.56	.53	.53
		3	.65	.62	.60	.61	.59	.59
		5	.69	.67	.65	.66	.65	.64
Bowl Frosted Lamp		1	.45	.42	.40	.41	.39	.38
		1½	.52	.49	.47	.48	.46	.46
		2	.56	.53	.51	.52	.50	.50
		3	.62	.60	.57	.58	.56	.56
		5	.66	.65	.63	.63	.62	.62
Opal Cap		1	.40	.37	.35	.37	.34	.34
		1½	.47	.44	.42	.44	.42	.42
		2	.51	.48	.46	.48	.46	.46
		3	.56	.54	.52	.53	.51	.51
		5	.60	.58	.57	.57	.56	.55
Clear Lamp		1	.36	.36	.34	.35	.33	.33
		1½	.45	.43	.41	.42	.40	.40
		2	.49	.47	.45	.46	.44	.44
		3	.54	.52	.50	.51	.49	.49
		5	.59	.57	.55	.56	.54	.54
Bowl Frosted Lamp		1	.37	.34	.32	.33	.31	.31
		1½	.43	.40	.38	.39	.37	.37
		2	.46	.44	.42	.43	.41	.41
		3	.51	.49	.47	.48	.46	.46
		5	.55	.53	.52	.52	.51	.50
Silver Cap		1	.33	.31	.30	.31	.29	.29
		1½	.39	.37	.35	.36	.34	.34
		2	.43	.41	.39	.40	.38	.38
		3	.47	.45	.43	.44	.42	.42
		5	.50	.49	.47	.48	.47	.46
Clear Lamp		1	.36	.31	.28	.30	.28	.27
		1½	.44	.39	.36	.37	.35	.35
		2	.50	.46	.42	.44	.41	.41
		3	.56	.53	.48	.51	.47	.47
		5	.62	.59	.54	.57	.53	.53
Shading Band		1	.38	.36	.34	.35	.33	.33
		1½	.44	.42	.40	.41	.39	.39
		2	.49	.47	.45	.46	.44	.44
		3	.54	.52	.50	.51	.49	.49
		5	.58	.56	.55	.55	.54	.53
Clear Lamp		1	.44	.41	.39	.41	.39	.38
		1½	.50	.47	.45	.47	.45	.44
		2	.55	.52	.50	.52	.50	.49
		3	.59	.57	.55	.56	.54	.54
		5	.63	.61	.59	.59	.58	.58
Clear Lamp		1	.36	.32	.29	.40	.37	.36
		1½	.54	.50	.47	.48	.45	.44
		2	.60	.56	.53	.54	.51	.50
		3	.67	.64	.61	.61	.58	.56
		5	.73	.70	.67	.67	.64	.62

FIG. 45.—Coefficients of Utilization.

196. Examples illustrating use of table of coefficients (Par. 195).

(*a*) Find the coefficient of utilization for an RLM dome, clear lamp, direct installation in a rectangular room 40 ft. × 120 ft.; ceiling height, 27 ft.; lamps mounted 20 ft. above the plane of work; plane of work 3 ft. above the floor; ceiling color, light; wall color, medium.

For a square room, narrow dimension,

$$\text{Room ratio} = \frac{40}{2 \times 20} = 1.00 \qquad \text{Coefficient} = 0.43.$$

For a square room, long dimension,

$$\text{Room ratio} = \frac{120}{2 \times 20} = 3.00 \qquad \text{Coefficient} = 0.62.$$

Coefficient of utilization for the rectangular room with RLM dome clear lamp units is then, $0.43 + \frac{1}{3}(0.62 - 0.43) = 0.49$. *Ans.*

(*b*) In the same room with an indirect, clear lamp installation, find the coefficient of utilization as follows:

For a square room, narrow dimension,

$$\text{Room ratio} = \frac{40}{1\frac{1}{3} \times 24} = 1.25 \qquad \text{Coefficient} = 0.21.$$

For a square room, long dimension,

$$\text{Room ratio} = \frac{120}{1\frac{1}{3} \times 24} = 3.75 \qquad \text{Coefficient} = 0.35.$$

Coefficient of utilization for the rectangular room with indirect, clear lamp units is then, $0.21 + \frac{1}{3}(0.35 - 0.21) = 0.26$. *Ans.*

Color (Reflecting Value) of Ceiling / Walls			Light (70%)			Medium (50%)		Dark (30%)
			Light (50%)	Medium (35%)	Dark (20%)	Medium (35%)	Dark (20%)	Dark (20%)
Reflector Type	Light Output	Room Ratio	Coefficients of Utilization					
Bowl-Frosted Lamp	90° to 180°—34% / 0° to 90°—51%	1	.34	.31	.28	.29	.26	.24
		1½	.41	.38	.35	.35	.33	.30
		2	.47	.44	.41	.40	.38	.35
		3	.53	.50	.47	.45	.43	.40
		5	.59	.56	.53	.50	.48	.45
Bowl-Frosted Lamp	90° to 180°—20% / 0° to 90°—80%	1	.40	.37	.34	.35	.33	.32
		1½	.47	.44	.41	.42	.39	.38
		2	.52	.48	.46	.46	.43	.42
		3	.58	.55	.52	.52	.49	.47
		5	.62	.60	.58	.57	.55	.52
With Reflector	90° to 180°—6% / 0° to 90°—94%	1	.31	.28	.26	.28	.25	.25
		1½	.37	.34	.32	.33	.31	.30
		2	.42	.39	.37	.38	.36	.35
		3	.47	.44	.42	.43	.41	.41
		5	.51	.49	.46	.48	.46	.45
Light Opal	90° to 180°—35% / 0° to 90°—65%	1	.23	.20	.17	.18	.16	.14
		1½	.30	.26	.23	.24	.21	.19
		2	.35	.31	.28	.28	.25	.22
		3	.41	.37	.34	.33	.30	.26
		5	.48	.44	.41	.39	.36	.31
Diffusing Bowl	90° to 180°—20% / 0° to 90°—80%	1	.32	.28	.26	.27	.25	.23
		1½	.40	.36	.33	.34	.32	.30
		2	.45	.41	.38	.39	.37	.35
		3	.52	.47	.44	.45	.42	.40
		5	.59	.54	.51	.51	.48	.46
Reflector and Bowl	90° to 180°—17% / 0° to 90°—83%	1	.32	.28	.26	.28	.25	.25
		1½	.39	.35	.33	.34	.31	.30
		2	.44	.40	.38	.39	.36	.35
		3	.49	.45	.43	.44	.41	.40
		5	.54	.50	.48	.49	.46	.45
Light Opal	90° to 180°—40% / 0° to 90°—25%	1	.27	.24	.21	.20	.17	.14
		1½	.34	.30	.27	.25	.22	.18
		2	.39	.35	.32	.29	.26	.21
		3	.45	.41	.38	.34	.31	.25
		5	.51	.47	.44	.40	.37	.29
Dense Opal	90° to 180°—70% / 0° to 90°—30%	1	.24	.21	.19	.16	.14	.10
		1½	.30	.27	.24	.20	.18	.13
		2	.34	.31	.28	.23	.21	.15
		3	.39	.36	.33	.27	.25	.18
		5	.45	.42	.39	.32	.30	.21
Diffusing Plate Bottom	90° to 180°—55% / 0° to 90°—45%	1	.25	.22	.20	.18	.17	.14
		1½	.30	.27	.25	.22	.21	.17
		2	.34	.31	.29	.26	.24	.19
		3	.38	.36	.34	.29	.28	.22
		5	.43	.41	.40	.33	.32	.24
Clear Lamp	90° to 180°—80% / 0° to 90°—20%	1	.22	.19	.17	.14	.12	.07
		1½	.27	.24	.22	.17	.15	.09
		2	.31	.28	.26	.20	.18	.11
		3	.36	.33	.31	.24	.22	.13
		5	.42	.39	.37	.28	.26	.16

FIG. 46.—Coefficients of Utilization.

197. Absorption of light in a given room

Surface	Lumens		
	Incident from all directions	Coefficient of absorption	Absorbed
Ceiling	280	0.14	39
Walls	672	0.57	382
36-in. horizontal plane	376	1.00	376
Total			797

198. Point-by-point method. The third method of computing illumination, the "point-by-point" method, is laborious but it is best calculated to yield results which are accurate in detail. By this method an exact computation is made of the intensity of light directed upon any surface by the lighting equipment, and to this is added an estimated amount for the diffused and indirectly reflected light which supplements the direct light.

199. Illumination intensity. The determination of intensity at any point when the distribution of light is known, involves the application of two fundamental laws, the inverse-square law (Par. **200**) and Lambert's cosine law (Par. **201**).

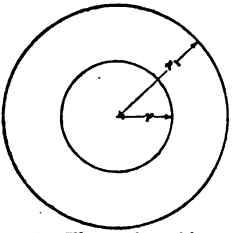


FIG. 47.—Illustration of inverse-square law.

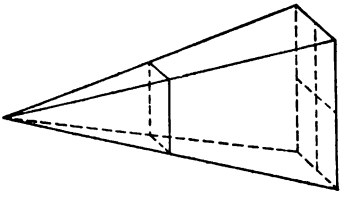


FIG. 48.

200. The inverse-square law (Par. 199) is demonstrated in Fig. 47 and 48 in which it is apparent that at twice the distance the given flux of light radiating from a point source covers four times as great an area and therefore its density is one-quarter as great. Proof of this law is as follows: let E = Intensity, in foot-candles; F = Flux, in lumens; S = Surface, in sq. ft.

$$E = \frac{F}{S} = \frac{F}{4\pi r^2} \tag{6}$$

$$E_1 = \frac{F}{4\pi r_1^2} \tag{7}$$

or

$$\frac{E}{E_1} = \frac{r_1^2}{r^2} \tag{8}$$

that is E varies as $1/r^2$.

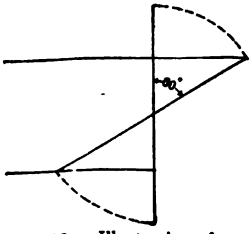


FIG. 49.—Illustration of cosine law.

201. Lambert's cosine law (Par. 199). If, however, the plane surface upon which the light falls is inclined from the normal, the flux of light incident upon the surface will vary as the Cos of its angle of inclination. This is known as Lambert's cosine law.

$$E = \frac{I \operatorname{Cos} \theta}{d^2} \tag{9}$$

where I is the candle-power, θ is the angle of inclination to normal, and d is the distance from source to surface. This reduction in incident flux due to inclination of the surface is illustrated in Fig. 49 in which it is seen that if the surface is inclined 60 deg. from the normal, the incident flux will be halved (Cos 60 deg. = 0.5).

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202. Table of squared and cubed cosines (Par. 203)

Angle (deg.)	Cosine		Angle (deg.)	Cosine	
	Squared	Cubed		Squared	Cubed
1	1.000	1.000	21	0.871	0.813
2	0.999	0.998	22	0.859	0.797
3	0.997	0.996	23	0.847	0.780
4	0.995	0.993	24	0.834	0.762
5	0.992	0.988	25	0.821	0.744
6	0.989	0.983	26	0.808	0.726
7	0.985	0.978	27	0.794	0.707
8	0.980	0.971	28	0.780	0.688
9	0.975	0.963	29	0.764	0.668
10	0.970	0.955	30	0.750	0.649
11	0.963	0.945	31	0.735	0.630
12	0.956	0.935	32	0.719	0.610
13	0.949	0.925	33	0.703	0.590
14	0.941	0.913	34	0.687	0.570
15	0.933	0.901	35	0.671	0.550
16	0.924	0.888	36	0.654	0.529
17	0.914	0.874	37	0.638	0.509
18	0.904	0.860	38	0.621	0.489
19	0.894	0.845	39	0.604	0.469
20	0.883	0.829	40	0.587	0.449
41	0.569	0.429	66	0.165	0.0673
42	0.552	0.410	67	0.153	0.0596
43	0.535	0.391	68	0.140	0.0526
44	0.516	0.372	69	0.128	0.0460
45	0.500	0.353	70	0.117	0.0400
46	0.483	0.335	71	0.106	0.0345
47	0.465	0.317	72	0.0955	0.0295
48	0.448	0.300	73	0.0855	0.0250
49	0.430	0.282	74	0.0759	0.0209
50	0.413	0.265	75	0.0669	0.0173
51	0.396	0.249	76	0.0585	0.0142
52	0.379	0.233	77	0.0506	0.0114
53	0.362	0.218	78	0.0432	0.00900
54	0.345	0.203	79	0.0363	0.00695
55	0.329	0.189	80	0.0300	0.00523
56	0.312	0.175	81	0.0244	0.00383
57	0.297	0.161	82	0.0194	0.00270
58	0.281	0.149	83	0.0149	0.00181
59	0.265	0.137	84	0.0109	0.00114
60	0.250	0.125			
61	0.235	0.114			
62	0.221	0.103			
63	0.206	0.0936			
64	0.192	0.0842			
65	0.179	0.0754			

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203. Computation of illumination intensity at any point. In computing the illumination intensity or flux density upon any surface, the distance from the light source to the surface is computed, the candle-power is divided by the square of the distance in order to obtain the normal illumination intensity, which is multiplied by the Cosine of the angle of inclination of the surface in order to obtain the flux density or illumination intensity for any desired inclination.

$$E_{nor.} = \frac{I_\theta \operatorname{Cos}^2 \theta}{h^2} \quad \text{in ft.-candles or lumens per sq. ft.} \quad (10)$$

$$E_{hor.} = \frac{I_\theta \operatorname{Cos}^3 \theta}{h^2} \quad \text{in ft.-candles or lumens per sq. ft.} \quad (11)$$

$$E_{vert.} = \frac{I_\theta \operatorname{Cos}^2 \theta \sin \theta}{h^2} \quad \text{in ft.-candles or lumens per sq. ft.} \quad (12)$$

where I_θ is the candle-power at stated angle, θ is the angle from the vertical and h is the height in feet above plane of reference. In such computation, the distance is obtained by triangulation and the formula is such as to leave the $\operatorname{Cos}^3 \theta$ the significant factor for computations of horisontal illumination and the $\operatorname{Cos}^2 \theta$ for computations of vertical illumination. In Par. **202** are given values of $\operatorname{Cos}^2 \theta$ and of $\operatorname{Cos}^3 \theta$ which will be of service in this connection.

204. Aids to computation of illumination. A number of graphical and mechanical aids to the computation of illumination have been devised.*

BRIGHTNESS

205. Definition of brightness. In Fig. 50 a diffusely reflecting surface which is uniformly illuminated, is viewed from position P through an aperture in a screen. The surface is located successively in three positions S, S_2 and S_3. In all positions it appears of the same brightness. Its brightness is independent of inclination or distance from the eye. The brightness

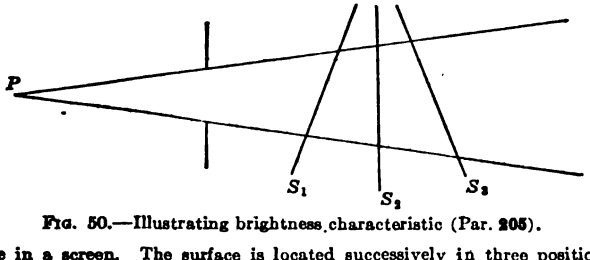


FIG. 50.—Illustrating brightness characteristic (Par. **205**).

* "Theory and Calculation of Illumination Curves," Benford, Illg. Eng. Soc., 1912.
"Graphic Solution in Problems Involving Plane Surface Lighting Source," McAllister, *Electrical World*, December 8, 1910.
"Graphic Solution for Illumination Problems," Dickinsen, *Electrical World*, September 20, 1913.
"Tables for the Computation of Illumination," published by Wm. E. King, Dorchester, Mass.
Weinbeer (Slide rule) *Illg. Engineer* (London), 1908, p. 559.
Macbeth (Calculator) *Illg. Engineer*, 1908, p. 21.
Computing Device, Eng. Dept., National Lamp Works, 1913.
These are of much assistance in work where numerous computations are to be made.

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of a surface which is not a perfect diffuser may vary with angle of view, but if it is large enough to cover the field of view, its apparent brightness will not vary with distance.

206. Relation of brightness to incident light. This may be stated only for a projected area of a perfectly diffusing plane surface for which $b = mE$ where b is the brightness; m is the coefficient of diffuse reflection; and E is the incident flux. Brightness is expressed in lamberts. A perfect diffusing surface emitting or reflecting 1 lumen per sq. cm. has a brightness of 1 lambert, equivalent to 2.054 candles per sq. in.

APPLIED ILLUMINATION

THE FUNDAMENTALS OF VISION

207. Contrast vision. We see things by reason of contour, relief and color, i.e., shade perception and color perception. According to Fechner's law of sensations we perceive a fixed fractional difference of the total, irrespective, within limits, of the amount of the total sensation, and the sensation is proportional to the logarithm of the stimulus. This minimum perceptible contrast is usually of the order of 1 per cent., and, with increasing brightness within wide working limits, the visual power increases but slowly

208. Color sensations. Ocular discernment as presented in the Young-Helmholtz theory is based upon three primary sensations: red, green and blue.

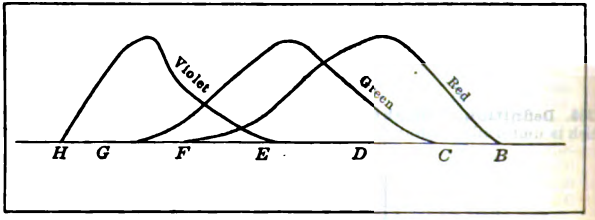


FIG. 51.—Primary color sensations.

violet, respectively. These overlap much as shown in Fig. 51, the curves of which show what color sensations will be stimulated by radiation of any given wave lengths within the visible spectrum. The seat of colar sensation is said to lie in the cones of the retina which are found almost exclusively in the fovea, the rods being limited largely to employment in twilight vision.

209. Protective equipment of eye. The protective apparatus of the eye against excessive radiation, consists, first, of the **pupil,** whose automatic response to changes in intensity of light under certain conditions are shown* in Fig. 52. It will be seen that the area of the pupil aperture does not alter sufficiently to protect the eye against effects of the large changes in illumination which it must encounter; the second protective element is to be found in retinal adaptation.

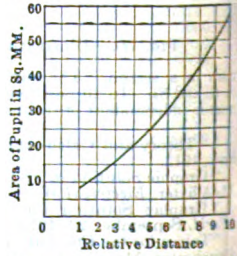


FIG. 52.—Reaction of pupil to variations in light.

210. Other ocular characteristics. Some of the physiological characteristics of the eye which are of importance in illumination work are as follows: (a) **adaptation,** the slow retinal change which supplements the rapid pupillary change both tending to adjust the eye

*Lambert's Experiments as reproduced in the "Art of Illumination" by Bell.

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or best vision under any condition of light intensity; (b) **induction**, the name applied to that effect of contrast which causes a dark surface to appear darker when in juxtaposition with a brighter surface or *vice versa;* (c) **Purkinje effect**, the tendency of the eye to become more sensitive to light of short wave lengths than to light of long wave lengths when the intensity is low. Due to the last-mentioned effect, with the same low intensity of light, blues and greens appear brighter than does red. See also Par. 10–12.

211. Threshold vision. In many ocular tests the point of minimum perception is the basis adopted. These are known as "threshold" or "limen" tests, and are applied to determine **visual acuity**, flicker, etc. Visual acuity is generally expressed in terms inversely proportional to the visual angle subtended by the observed object at threshold value, unity being taken as an angle of 5 min. Visual acuity is tested by determination of the smallest discernible object, as a letter, under a given low intensity of illumination; or the greatest distance at which a given object under a given intensity of illumination may be discerned; or the minimum illumination at which a given object at a given distance may be discerned. **Flicker tests** usually consist in the determination of the minimum change in intensity upon an observed object which may be perceived with a given rate of flicker, or the minimum rate of flicker which may be detected with a given change in intensity. Threshold tests of shade perception are also applied. The line of division between such tests and visual acuity tests is not clearly indicated, since some visual acuity tests in one sense are shade perception tests. In all such tests the accuracy attained is of a lower order than that attained in comparison tests where one surface is brought to the same brightness as another surface in juxtaposition to it.

212. Psychology of vision. Vision is a combined physiological and psychological process. For example, the eye as an optical instrument produces upon the retina an inverted image of an object viewed. This applies the stimulus to produce the sensation. The mind interprets before the object is rightly perceived. Therefore the subjective phenomena associated with vision are of prime importance; unfortunately they are but little understood by lighting practitioners. The observer's conception of the appearance of objects, images of which are impressed upon the retina, depends upon the mental interpretation of such images in the light of tradition, memory and experience.

CHARACTERISTICS OF ILLUMINATION

213. Steadiness vs. fluctuation in light. Reliability in an illumination system is a first requisite. Of a like obvious character is steadiness. Unsteadiness is distressing and perhaps injurious to the eyes in spite of the protective features with which they are provided. Unsteadiness of light, as encountered in flames which fluctuate with atmospheric disturbances, is not found in electric illuminants as a rule, though arc-lamps exhibit somewhat similar tendencies. Unsystematic fluctuations in the arc may be due to a wandering of the arc. This propensity changes the light-distribution characteristics, notably in the open carbon-arc lamp; or results in vaporising a more or less luminous material from the electrode, as in the flame-arc lamp and metallic-electrode lamp. Requirements in indoor lighting are such as to bar badly fluctuating light sources from general use. The requirements for exterior lighting are less rigorous in this respect, and therefore arc-lamp fluctuations which could not be tolerated for most indoor purposes, do not constitute serious objections for some classes of exterior lighting.

Incandescent lamps are subject to unsystematic light fluctuations only when operated upon a circuit which carries a varying power load as, for example, elevator motors. **Systematic light fluctuations** occur on alternating-current service. Incandescent lamps are characterized by greater thermal stability than arc-lamps, and these cyclic light fluctuations are therefore less serious. For incandescent lighting, 35 cycles appears to be the approximate lower frequency limit for satisfactory service of all classes, though for many purposes 25 cycles lighting has been found satisfactory.

214. Intensity or flux density is an all-important fundamental to be considered in illuminating practice. Sufficient intensity of light must be

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provided to serve utilitarian purposes, to enable the eyes to accomplish their function without undue fatigue, and to create pleasing effects—three purposes which must be served in the order of their importance in all installations. To accomplish this it may be necessary to provide an illumination of uniform intensity, or the flux may have to be distributed dissymmetrically. Shadows are important, contrasts must be correct and a careful study of the intensities necessary to produce brightness of the right order is essential to success in lighting installations.

215. Illumination intensities for various classes of service. Experience is teaching that economy is promoted by the adoption of much higher intensities in industrial work than have heretofore prevailed. Every reported experiment shows increased production, diminished shrinkage and satisfied employer and employee when a change to higher intensities has been made in installations where the judgment of competent engineers has guided the selection. But there is lacking information to show whether such higher intensities are lower than or higher than the intensity yielding the greatest economy of production. The best guide available at the present time is to be found in the Code of Lighting of the Illuminating Engineering Society and in the several State Industrial Lighting Codes which are modeled upon the Society Code. Some of the state codes prescribe detailed minima for a variety of industrial operations. The Code of the State of Oregon shows preferable intensities for a great variety of operations. Some representative values are given in Par. **219.**

216. Direction. The best direction for the strongest component in any illumination system is peculiarly a matter for determination after study of local conditions. In natural lighting there is usually a strongly directed component, the only exception being a condition of diffused light such as that produced by mists, rain, etc. A great variety of directions for this principal component is experienced, ranging from one almost directly downward at mid-day in the summer to one which is almost horizontal just after sunrise or just before sunset. It is probable that the most pleasing direction for daylight conditions lies well between these two extremes.* The direction of light in interiors illuminated from side windows is unnatural and in many instances is neither pleasing nor comfortable. This is especially true of offices in high buildings where nothing but the sky is visible through the window from a point well in the interior of the room.

217. Direction of light affects appearance. A suitable direction for light is very important in industrial work where the avoidance of shadows and the avoidance of glare are of paramount importance. The appearance of a room is very largely dependent upon the direction of the light.† In ornamentation, relief designs are absolutely dependent upon the relation of light and shade.‡ Usually they require not only a noticeable directed component but also they require that the direction of that component shall be correct. So also, in the general appearance of a room and of the objects contained in it, shadows are important and their proper direction is a prominent factor in determining the final appearance of the room. The direction of incident light is, to some extent, a determining factor in the extent and characteristic of the reflection from surfaces.‖

218. Diffusion. See Par. **220.** If light from a point source passes through crystal glass or is reflected by a mirror, the rays are uniformly divergent, that is characteristically radiating. If the crystal glass or the mirror be replaced by an etched glass and a mat reflecting surface respectively, the uniform radiating characteristic is lost, the rays are scattered, and further propagation takes place in a multiplicity of directions. Such light is called

* "Distribution of Luminosity in Nature." Ives and Luckiesh, Trans. Illg. Eng. Soc., 1911.

† Ives. "Some Home Experiments in Illumination," Trans. Illg. Eng. Soc., 1913, p. 238.

‡ Luckiesh. "Importance of Direction, Quality and Distribution of Light," Proceedings American Gas Institute, 1913.

‖ "The Effect of Variation of the Incident Angle on the Coefficient of Diffuse Reflection." Gilpin, Trans. Illg. Eng. Soc., 1910.

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diffused light. If the surface which occasions the diffusion is of large area and the illuminated object is relatively close to the diffusing surface, it is illuminated by diffused light. If, however, the object is relatively far removed from the diffusing surface, it is illuminated by light from essentially one direction, the rays are nearly parallel, and the light is but little diffused. Hence, diffusion is a relative term, and the subject is difficult to treat in a definite way.

219. Illumination intensities prescribed in factory lighting codes

Operations	I. E. S. Code, 1917, "Ordinary Practice"	New York State,* 1918 "Minima"	Oregon Code, 1919, "Preferable Intensities"
Rough manufacturing:			
Machining, assembling, punch work, etc., foot-candles	2–4	.....	.....
Foundries:			
Fine molding, grinding, machine molding, foot-candle	.....	1	.....
Core making	.....	2	.....
Foundries, foot-candles	.....	.....	1–9
Rough manufacturing involving closer discrimination of detail, foot-candles	3–6	.....	.....
Fine manufacturing:			
Lathe work, pattern and tool making	4–8	.....	.....
Light colored textiles, etc	.....	.....	3–12
Jewelry	.....	5	8–†
Printing:			
Job presses	.....	1	3–12
Lithographing	.....	2	.....
Engraving	.....	5	.....
Shoe manufacturing:			
Most processes	.....	2	.....
Inspection and finishing	.....	5	.....
Light	.....	.....	3–12
Dark	.....	.....	8–†
Electrical manufacturing	.....	.....	4–12
Special fine work:			
Watch making, engraving, drafting, dark colored textiles, etc	10–15	.....	8–†
Dark colored textiles:			
Most processes	.....	1	.....
Weaving, knitting, inspecting	.....	2	.....
Office work	4–8	.....	4–12
Stairways, passageways, halls	½–2	.....	.....
Storage spaces	½–1	.....	.....
Roadways and yard thoroughfares	~~1/10~~–½	.....	.....

220. Various degrees of diffusion. See Par. **218**. Perfect diffusion of light is obtained within a hollow sphere whose inner reflecting surface is mat. Some plane-reflecting surfaces are nearly, if not quite, perfect diffusers of light. Perfect diffusion may be represented graphically by a circle, tangent upon the diffusing surface. Imperfectly diffused transmission or reflection

* Tentative and not at present mandatory.
† Upper limit not decided upon.

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may be represented by various curves having radials elongated in the direction of regular transmission and reflection, indicating correspondingly less distribution in other directions than is provided by perfect diffusion. A variety of reflection characteristics is illustrated in Fig. 53, ranging from perfect diffusion to a combination of regular and diffuse reflection characteristic of glossy paper.

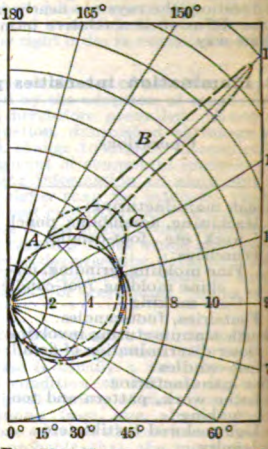


FIG. 53.—Various degrees of diffus reflection. Light incident 45 deg. b low horizontal, surface being vert cal. A, perfect diffusion; B, reflec tion from glossy paper; C, reflectio from semi-glossy paper; D, reflectio from mat paper.

221. Need for diffusion. Diffusion tends to avoid glare and to soften shadows. Its accomplishment involves the substitution of secondary light sources which are relatively large and therefore of low brightness when compared with the source of light. Artificial lighting is usually inferior to natural light in respect to diffusion.† In practically every installation there is a real necessity for introducing artificial means of diffusing the light.

222. Color in its physical aspects has been treated in the discussion of the production of light (Par. **27**). The spectrophotometric values of light from the several common illuminants have been supplemented by color-sensation values as determined with color-mixing instruments. Referring further to the subject in its physiological relations, it may be noted that there are three primary colors, namely: red, green, and blue-violet, using pure spectrallight. With these three colors, light of any desired color value may be produced. In his ability to modify the color of light, the illuminating engineer has at his disposal a means of enhancing the attractiveness of an interior as will be brought out more in detail under discussion of congruity in illumination, Par. **232**. It also is field in which there is an opportunity for profiting by certain peculiarities o vision (Par. **208**).

PHYSIOLOGICAL AND PSYCHOLOGICAL EFFECTS OF ILLUMINATION

223. Contrast. Once the correct general intensity of light (Par. **216**) is secured, all other aspects involved in direction (Par. **217**), diffusion (Par. **218**) and color (Par. **222**) as well as in the distribution of the light to produce various intensities, must be so manipulated as to secure the proper degree of contrast. The more the subject of good illumination is considered, the more prominently does contrast force itself upon attention as a fundamental which must be served if an installation is to be successful. This applies both to contrast of light and shade and to contrast of color. Contrast of light and shade resolves itself into a question of varying brightness, embracing the range of brightness values from a brilliant incandescent-lamp filament or an arc, down to the deepest shades within view. The unshaded

* Nutting. "The Diffuse Reflection and Transmission of Light," Transactions Illg. Eng. Soc., 1912.

† Luckiesh. "Investigation of Diffusing Glassware," *Electrical World*, Nov. 16, 1912 and April 26, 1913.

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incandescent lamp glowing outdoors in the daytime does not appear very bright against a background of sky, and may be viewed directly without discomfort. The same unshaded lamp burned at night in a room which is decorated in light colors, will prove annoying, while if burned in a room of which the decorations are of low reflecting quality, as dark woodwork, the lamp will prove positively intolerable. In the three cases the brightness of the lamp remains the same, and it is the varying contrast with its surroundings which explains in the one case, absence of discomfort and in the other extreme case, the most serious kind of ocular discomfort.

224. Need for concealing light sources. In Par. 31 brightness values for various unshaded light sources are given. It will be observed, for example, that these range from less than one candle-power per sq. in. for the Moore tube to 4,000 candle-power per sq. in. for the magnetite arc. This is, indeed, a wide range in brightness. When, however, it is remembered that the brightness of a very well-lighted wall, decorated in some light tone is of the order of 0.003 candle-power per sq. in., it will be seen that the variations in brightness of commercial light sources are small in comparison with the contrasts between any of them and the surfaces with which they are likely to be surrounded in practice. Herein lies the necessity for shading light sources in order to protect the eye against excessive contrasts. Entirely capable of protecting itself against excessive brightness, the eye is not able to see the objects of relatively low brightness and at the same time guard itself against the very high brilliancy of an exposed light source. There still remains the necessity for avoiding the intrusion of reflected images of the light sources in the ordinary field of view. A well-shielded light source may be exposed in the direction of a polished table top, the surface of which may reflect an image of the light source, subjecting the eye to almost as great strain as though the actual source were exposed. Glossy paper, shiny materials to be worked upon, polished woodwork, etc., are likely to introduce this sort of difficulty. Nature's surfaces as a rule are not shiny; artificial surfaces are likely to be shiny. In abolishing glossy paper, polished woodwork, etc., a long step is taken toward the elimination of excessive contrasts in artificial lighting. It is not possible, however, to abolish all such surfaces, and in other cases it is not done. It is, therefore, desirable to conceal the light source further. Accordingly, the improvement of a few years since in providing translucent reflectors which largely cover incandescent lamps and shield them from direct view, has been supplemented more recently by frosting the lower part of the bulbs of the lamps and the interior surfaces of the reflectors in order to soften and diffuse the light. Consequently, when reflected images are encountered, their brightness is rendered of as low an order as practicable. More recently still, bowls have been employed, either opaque or translucent, which intervene between any point of observation and the light source proper, softening and diffusing the light and directing a part or all of it toward the ceiling, whence it is further diffused and reflected downward.

225. Glare due to light source. Excessive brightness and light out put of surfaces or objects within the field of view give rise to glare. Where the light source itself is within view, or a more or less imperfect image is viewed upon a polished surface, the effect is much the same (Par. 223). Glare may actually reduce one's visual power temporarily; it may occasion discomfort and eyestrain; or if continued long enough, it is thought likely to impair visual organs. The effect of temporary reduction in visual power has been studied extensively.* In Fig. 54 is shown the reduction in visual power due to the presence of an exposed lamp in a dark room. The observers viewed a dimly illuminated test object. The presence of a 16-candle-power bare lamp 2 deg. from the test object reduced the observer's ability to discern the test object to about the same extent as would follow a reduction in illumination of 80 per cent. As the light source was removed from the observed object, its detrimental influence became less marked, falling off rapidly until the angle of separation was 4 deg., and thereafter at a slower,

*Sweet. "An Analysis of Illumination Requirements in Street Lighting," Journal of the Franklin Institute, May, 1910.

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rate until at about 15 deg. the effect disappeared. Because of the ver exaggerated conditions of dark surroundings and dimly illuminated te object, the results here obtained show diminished visual power far beyon that which would likely be experienced in practice. They illustrate th effect, however, and are suggestive of the need for concealing the light sourc It is to be noted that, though no reduction in visual ability could be mea ured when the source was removed 15 deg. from the centre of the field view, yet the discomfort and annoyance due to its presence were very sever

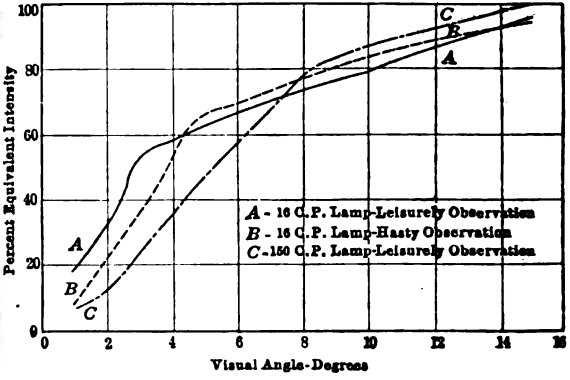


FIG. 54.—Influence of glaring light source in decreasing visual powe

226. Glare due to reflected image of light source. Glare due to image of light sources reflected from shiny surfaces is probably more productiv of harm in the present stage of practice than is glare directly due to exposed light sources. While the imperfect rendering of the image by th usual polished surfaces decreases the brightness materially, yet the loca tion of the reflected image is often so near the centre of the field of vision a to be much more serious than an exposed light source further removed. Viewing a glossy paper at the critical angle in which the image of the ligh source is reflected to the eye, it may be impossible to read print. This effect is diminished by altering the position of the object or of the observer, but, du to minute irregularities of the surface of the paper, there is still likely to b an appreciable regular reflection toward the eye. Likewise, paper which is only slightly glossy may reflect regularly toward the eye an appreciable section of the image of the light source without introducing so serious an effect as to prompt the observer to change position. Such conditions are the source of much discomfort and dissatisfaction experienced in artificial light ing. If they are to be avoided, light sources must be shielded both from immediate observation and from possibilities of reflection from glossy surfaces.

227. Reflection Factors. If it be assumed that softly diffused light is distributed generally throughout an interior producing uniform illumina tion, contrasts are dependent wholly upon the reflecting qualities of the illuminated surfaces. As these are usually less readily changed than the distribution and quality of the light, it is desirable to consider them before determining upon the degree of uniformity which should be achieved in light distribution. Uniform illumination with uniform decorations in an interior would be undesirable from every standpoint. Uniform illumination with heavily contrasted decorations and fittings may be acceptable. It is there fore of interest and value to obtain information on the reflection factors of various surfaces, such are contained in Par. **228.**

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228. Reflection factors with light from tungsten-filament lamps

Color	Finish	Kind	Flux incident at 60 deg.	45 deg.	30 deg.	15 deg.	0 deg.	Mean
Papers*								
White	Mat (smooth)	Pulp tint	56	61	58	57	55	57
Light buff	Mat (smooth)	Pulp tint	46	47	46	44	43	45
French gray	Semi-glossy	Silk fibre	38	32	26	23	21	26
Light brown	Semi-glossy	Silk fibre	17	15	12	11	10	13
Light blue	Semi-glossy	Silk fibre	15	13	10	9	8	11
Cherry red	Semi-glossy	Silk fibre	14	12	9	7	6	10
Yellow buff	Rough	Plain	31	34	36	36	35	34
Cream	Glossy	Varnished tile	66	71	73	72	71	71
White	.....	Blotter	73	80	74	73	71	74
Paints†								
White	Flat	.....	71	.....	69	.....	66	69
White	Glossy	.....	89	.....	70	.....	63	74
Cream	Flat	.....	56	.....	54	.....	51	54
Ivory	Glossy	.....	78	.....	62	.....	52	64
Aurora-yellow	Flat	.....	29	.....	30	.....	30	30
Fresco-gray	Glossy	.....	33	.....	19	.....	11	21
Pompeian-red	Flat	.....	10	.....	8	.....	8	9
Silver-gray	Semi-glossy	.....	35	.....	30	.....	25	30
Sky-blue	Glossy	.....	54	.....	31	.....	25	37
Sage-green	Glossy	.....	62	.....	48	.....	39	50

* Gilpin. *Trans.* Illg. Eng. Soc., 1910, p. 854.
† Jordan, *Trans.* Illg. Eng. Soc., 1912, p. 543.
See also Harrison and Anderson, *Trans.* Illg. Eng. Soc., 1919.

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229. Shadows. Further contrasts are encountered in shadows. The more generally the light is distributed; the lighter are the shadows; the more generally the light is diffused, the less sharp are the shadow contours. Both depth of shadow and sharpness of outline are of importance in contributing to the effect of contrast. When properly treated, relatively deep shadows are of importance in contributing to perspective and in producing a satisfying effect. In some kinds of industrial work, in office work and in some other classes of work all but very soft shadows should be avoided. Rolph* has concluded that for working surfaces when the shadow has sharply defined outline, it should not be more marked than 15 per cent., while if the outline is quite indefinite, as with well-diffused lighting, it may be as much as 50 per cent.

230. Color contrast. The remaining aspect of contrast is the important one of color. Pleasing color contrasts are of value in affording rest for the eye, in lending perspective, and in preventing monotonous effects. The color effect of a given surface depends to no little extent upon the color of other surfaces in the field of view with which it is contrasted. Also, very slight modifications of the light may produce marked changes in the appearance of the colored surfaces. The choice of the correct color for the light employed in a particular case is therefore essential to successful illumination from the decorative standpoint.

231. Permissible contrasts. In general, authorities state that brightness objects to which the eye is subjected should not exceed 4 or 5 c-p. per sq. in. (0.62 to 0.78 c-p. per sq. cm.) if physiological requirements are to be met. This applies to interiors at night. The limitation is relative rather than absolute. One authority,† while asserting the impracticability of fixing a standard, suggests that if the brightness of the object upon which the eyes are employed is of the order of 10 times that of surrounding objects, physiological requirements will be met satisfactorily.

232. Congruity. The requirements of esthetics are for illumination and an illuminating equipment which shall be pleasing to the senses and in harmony with the character of the premises illuminated. In buildings of notable architectural design the equipment should not only be suitable for its surroundings but the illumination should produce such combinations of light and shade, such contrasts, such color effects as will bring out in true proportions the important architectural features of the building, and will render its ornamentation in the manner conceived by the architect. In churches the illuminating equipment and the illumination must be of a character which is in keeping with the religious purposes for which the building is designed. In manufacturing establishments, effective illumination should be provided from simple, practical equipments. Incongruity of fixture, auxiliary, or illuminant; or unsuitability of light in quality, intensity, direction, etc., may mar an otherwise efficient illuminating system.

233. Pigmentary colors. Color of light, like color in decoration, is an aspect which affords many opportunities for skillful use by the illuminating engineer. In pigments, red, yellow, and blue of certain kinds and in certain proportions will produce white or any other desired color. They are sometimes referred to, therefore, as the primary colors, though, in a scientific sense, pure prismatic colors, respectively, red, green, and blue-violet, are the primary colors. The colors used for decoration are, however, dependent for their appearance upon the quality of the light by which they are illuminated.

It will be obvious, of course, that pigments which appear to the eye similar as regards color may be quite different physically, and that therefore their rendering under light of various colors may be markedly different from that here indicated. This is a field of application in which nothing may be taken for granted; only by trial can the appearance of a given pigment under a given light be determined. In decoration, therefore, a knowledge of the quality of the light employed is of first importance, It is essential that light be provided of such color value as will produce the effect desired in decoration.

* Rolph. *Trans.* Illg. Eng. Soc., 1912, p. 242.

† Cobb. "Physiological Points Bearing on Glare," *Trans.* Illg. Eng. Soc. 1911.

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234. Ultra-violet light. Some alarm has been felt by physiologists st ultra-violet light from our ordinary illuminants should prove harmful to e visual organs. It appears to be quite clear, however, that nothing of this nd is to be feared. Recent investigations* show that little is to be appre- ended on this score. The ultra-violet radiation from commercial illumi- ants is shown in Par. **235**.

The data in this table arrange illuminants according to their ultra-violet, diation. Luckiesh, studying the same subject at about the same time, rived at the following conclusion:

"It appears that when glass is used over any commercial light source there n be very little harmful effect when moderate intensities are used. Consid- ing the greater intensities of daylight, protection, if necessary in any case, is ally needed against it rather than against artificial illuminants except in the se of special use of the latter light sources."

METHODS OF ILLUMINATION

236. Direct lighting. The fact that light sources are usually placed gher than the surfaces to be illuminated and that a downward direction of e light is rather generally desirable under such conditions, has led to the

235. Ultra-violet radiation

Light source	Ergs per sec. per sq. cm. per foot-candle
Quartz arc ("Alba" globe)	4.3
Graetzin	11.7
"Gem" lamp, 100-watt	14.8
Cooper Hewitt (glass)	15.5
Sunlight (direct)	16.1
Acetylene flame	18.4
Tungsten lamp (100-watt)	22.7
Nernst lamp (globe)	25.5
Magnetite (glass)	30.3
Magnetite (quartz)	36.3
Old-quartz lamp (bare)	38.3
New-quartz lamp (bare)	87.6
Carbon arc (quartz)	91.0

ommon use of inverted-bowl or cone-shaped reflectors. These have been iscussed at length in Par. **131** of this section. The fact that much of the ght of such equipments is reflected toward the objects to be illuminated ithout the interposition of reflecting or transmitting media, has led to the doption of the term "direct lighting" for installations so equipped. The mployment of direct-lighting equipments usually facilitates the delivery of a naximum percentage of the total light upon the surfaces to be illuminated. o important has it been considered to promote this end, that the term "effi- iency of utilization" (Par. **188**) has sometimes been applied to the ratio of ight delivered upon a working plane to total light produced within a room. This term has sometimes been applied to such ratios in installations where he importance of illuminating other surfaces is as great or greater than that of illuminating a working plane. Such misuse of the ratio of light delivered upon the working plane to light generated has brought it into disrepute, which has been the greater because of occasional application of the term "illuminating efficiency." This term is especially inappropriate by reason of the fact that other considerations than intensity of light have come to be regarded as of perhaps equal importance, though they are disregarded in arriving at the "illuminating efficiency" by the method indicated above. The ratio of utilization, or the per cent. of light flux delivered upon a working plane, other things being equal, is greater when direct-lighting equipment is employed than under other circumstances. It is more difficult, however, to

* Bell. *Electrical World*, April 13, 1912.
Luckiesh. *Electrical World*, June 15, 1912.

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obtain that degree of diffusion of light which is essential to the avoidance of glare and the elimination of excessively deep shadows. Direct-lighting equipment does not always yield, therefore, the most effective illumination obtainable from a given amount of light produced within a room.

237. Indirect lighting. Some of the worst difficulties encountered in the use of direct-lighting equipments were eliminated by the use of so-called "indirect-lighting equipments," in which the light sources are entirely concealed from view and the light is directed upon a reflecting surface such as the ceiling, which reflects and diffuses it. The reflecting surface in such systems becomes the apparent light source, and, being of large area, its brightness is very much lower than that of the real source. In consequence, shadows are softened, immediate glare effect is much diminished, and glare due to reflection from specular surfaces is likewise diminished. Indirect-lighting equipments produce conditions which are much more conducive to comfortable vision than are those usually attending the use of direct-lighting equipments. It is, however, much more difficult to control the light, and a much greater portion of the light is usually lost before becoming effective.

238. Semi-indirect lighting. Equipments intermediate between these two in respect to effectiveness of light direction, diffusion of light, softening of shadows and reduction of glare, have been classed broadly as "semi-indirect lighting" equipments. These consist usually of translucent bowls, translucency varying widely and brightness of bowl varying in a corresponding manner. In point of fact there is very little difference between lighting effects obtained with some indirect-lighting equipments and some semi-indirect lighting equipments because, in both, large proportions of the light are directed toward the ceiling, whence they are diffused throughout the room. Enclosing globes also are likely to produce results of much the same order. When the translucency of the semi-indirect bowl is so low that the brightness of transmitted light is not greater than that of the ceiling, the lighting effects are likely to be quite similar to those which obtain when indirect-lighting fixtures are employed.

239. Intermediate types of lighting equipment. In brief, opaque reflectors which allow little light to be distributed elsewhere than upon the working plane are distinctively direct-lighting equipments and form one extreme of a range upon the other extreme of which indirect-lighting equipments may be placed. Between these two extremes are a great variety of equipments, all of which distribute part of the light upon the ceiling and part of it downward. It is difficult to differentiate among these intermediate equipments from the standpoint of illuminating results. Most such equipments, however, may be located in one of three classes, namely: (a) inverted bowls or cones; (b) totally enclosing glassware; (c) translucent bowls.

240. Local illumination. The tendency in recent years has been to depend upon general lighting as far as possible and to supplement it by local illumination only where unavoidable. It is well to do so because with local illumination it is difficult to avoid glare either from the source directly or from the illuminated surface. When, however, it is necessary to illuminate locally some surface, which must be very brightly lighted, every precaution should be taken to avoid the evils just named. The application of diffusing media and care in locating the light source will go far toward accomplishing this; and satisfaction is doubly assured if, in addition, there is an ample general illumination supplementing the local illumination.

ILLUMINATION DESIGN

241. The purpose to be served. In laying out an installation a first step—so simple and obvious that its mention might appear unnecessary—is to determine the purposes to be served by the lighting installation. Usually one does not simply "light a room." He provides lighting in order to make store attractive to the prospective customer and to promote the sale of goods; to illuminate the work on the machine and promote its prompt, accurate and safe accomplishment; to facilitate clerical work, promoting speed and accuracy without fatigue to the clerks; or to enhance the beauty and charm of a room in a residence. As a rule there are two or more principal objects to be attained in every installation. And the practitioner who familiarises himself thoroughly with the conditions underlying the requirements established by these objects takes the first essential step in successful lighting design.

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242. Choice of illuminant. Usually general conditions narrow the choice to two or three illuminants. In a residence any other illuminant than incandescent lamps would be unsuitable. In a steel mill the choice would probably be narrowed to Type C Mazda or mercury lamps. In a store either Mazda lamps or intensified carbon arc lamps would be employed, etc. In a street either magnetite or Type C Mazda lamps would probably be considered. Reliability, simplicity, efficiency, color of light, steadiness, cost (first, operating and maintenance) and size usually determine this choice.

243. Choice of auxiliary. Cost, ease of cleaning, ruggedness, efficiency new and maintained, light-directing qualities, diffusion, color, size and appearance have to be considered. Obviously, the importance of each qualification depends upon the nature of the installation.

244. Spacing and height. In industrial and commercial lighting it is generally considered that the spacing should be something like 50 per cent. greater than the vertical distance from the plane of illumination to the light source. This is a sufficiently good relation to form a point of departure in planning an installation. In large rooms it is useful to divide the floor area into squares or approximate squares. Desirable sizes of these squares are given in Par. **245**.* One light source may be placed over the middle of each such square. Often, however, the squares or rectangles which form the unit of space to be lighted are established by the confines of the room or by the pillars or beams which make the division of the room into bays. In such cases it may be practicable to treat the space as a unit or it may be necessary to subdivide it into say four rectangles. Where uniformity of illumination or a distinctly downward direction for the light is desired, smaller rectangles should be adopted. Other things being equal, smaller rectangles should be used for direct lighting and larger ones for indirect lighting because in the latter case, the actual light source (ceiling) is higher and the diffusion is greater. In general, the adoption of smaller rectangles, which means more frequently spaced smaller light sources, results in greater uniformity less marked shadows and less glare, while larger rectangles and larger illuminants afford more pleasing appearance. Balance between these two depends upon local conditions.

245. Desirable sizes of squares

Kind of room	Ceiling height	Desirable length of side of square
Armories	12 to 16 ft.	12 to 16 ft.
Auditoriums	12 to 16 ft.	12 to 16 ft.
Public halls	Over 16 ft.	15 to 26 ft.
Rinks	Over 16 ft.	15 to 26 ft.
Stores	8 to 11 ft.	8 to 11 ft.
Stores	11 to 15 ft.	10 to 16 ft.
Stores	Over 15 ft.	14 to 22 ft.
Offices—with desk lights	10 to 20 ft.	12 to 18 ft.
Offices—without desk lights	9 to 12 ft.	7 to 11 ft.
Offices—without desk lights	12 to 16 ft.	9 to 14 ft.
Offices—without desk lights	Over 16 ft.	11 to 18 ft.

246. Amount of light to be provided. Assume that it is desired to light a room which is 20 by 12.5 ft. and 12 ft. high. The ceiling is white and the walls are buff. An average horizontal illumination of 4 foot-candles or lumens per sq. ft. is desired. Under such conditions it is reasonable to estimate that 50 per cent. of the light flux produced in the room can be delivered upon a horizontal plane with sufficient diffusion for most purposes, and with ample light upon ceiling and walls. About 30 per cent. should be allowed for deterioration due to dust, etc. Therefore the light to be delivered upon the 30-in. horisontal plane is to be considered as about 35 per cent. of the total light to be produced. The area of the room is 250 sq. ft. (20 by 12.5 ft.). This multiplied by 4 foot-candles, or lumens per sq. ft., yields 1,000 lumens, which, being 35 per cent. of the total to be produced, gives 2,860 lumens as an approximation of the total flux required.

*"Handbook on Incandescent Lamp Illumination," General Elec. Co., 1913.

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A check upon the correctness of this estimate is had by the absorption of light method (Par. **196**).

Surface	Area	Estimated average foot-candles	Estimated coefficient of absorption	Lumens Absorbed
Ceiling.....	250 sq. ft.	1	0.3	75
Walls.....	780 sq. ft.	1½	0.6	702
Floor.....	250 sq. ft.	4	0.9	900
Total				1,677
Allowance for 20 per cent. loss in reflector				419
Allowance for 30 per cent. deterioration				898
Total				2,994

As Mazda lamps produce about 10 lumens per watt it would appear that the required illumination could be obtained in the hypothetical room from either three 100-watt or two 150-watt lamps. To permit symmetrical arrangement the latter would probably be chosen and would be installed, each over the middle of a 10-ft. rectangle with a separation of 10 ft. If a plane of reference be chosen as 30 in. above the floor and the lamps be mounted 9 to 10 ft. above the floor, no difficulty will be met in selecting translucent reflectors whose light distribution will provide substantially uniform illumination over the plane selected. To study in detail the curve of illumination to be obtained apply methods of point to point calculation as described in Par. **198** and add a uniform increase of, say, 10 per cent. of the average, to represent the light reflected from ceiling and walls.

247. Illumination of several classes of installations. No attempt can be made here to discuss the special design features of the several classes of lighting installation. Those interested in the subject are referred to the Transactions of the Illuminating Engineering Society and to the technical press for descriptive articles. An index to some of the more important articles which may be consulted in this connection, is given in Par. **249**.

COSTS

248. Calculation of total operating cost.* "In determining the total operating cost of any system of lighting, three items should be considered: (a) fixed charges, which include interest on the investment, insurance and taxes, depreciation of permanent parts, regular attendance, and other expenses which are independent of the number of hours of use; (b) maintenance charges, which include renewal of parts, labor, and all costs, except the cost of energy, which depend upon the hours of burning; (c) the cost of energy, which depends upon the hours of burning and the rate charged.

"If data are compiled under these heads in convenient units, such as in (a) an annual charge, in (b) a charge per 1,000 hr. operation, and in (c) a charge per 1,000 hr. operation at unit cost of energy, the several items may easily be calculated for any given set of conditions, and the total annual operating cost of any lighting system obtained as their sum.

"Under fixed charges, the items of depreciation and attendance may be mentioned particularly. Depreciation should be charged on permanent parts only, and not upon parts the renewal of which is provided for in the maintenance cost. The rate for depreciation should, in many cases, be higher than the current practice, for obsolescence, rather than the wearing out of parts, determines the life of a lighting system. There are many installations in use to-day which are in good order and giving a fair measure of satisfaction, but which could be replaced at a large saving.

"Too much emphasis cannot be given to the desirability of regular attendance for those illuminants which do not require trimming from time to time. It is essential for satisfactory operation that such lamps and reflectors be

*Harrison and Magdsick. "The Analysis of Performance and Cost Data in Illuminating Engineering," *Trans.* Illg. Soc., 1911.

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249. Selected list of references pertaining to illumination design

Author	Where published	Title
Industrial lighting		
Marks	Trans. I. E. S., 1909, p. 805.	Factory Lighting.
Stickney	Trans. A. I. E. E., 1910, p. 229.	Illumination of Industrial Plants.
Eshleman	Trans. A. I. E. E., 1911, p. 41.	Industrial Lighting.
Clewell	Trans. A. I. E. E., 1912, p. 1321.	
Industrial Commission of Wisconsin, 1914.		Handbook on Shop Lighting.
National Lamp Works, G. E., Co	Bulletin 20A, 1919.	Industrial Lighting.
Cooper-Hewitt Electric Co	Bulletin, 1921.	Principles of Industrial Lighting.
Edison Lamp Works, G. E. Co	Bulletin 43402, 1914.	Lighting of Machine Shops and Metal Working Plants.
Edison Lamp Works, G. E. Co.	Bulletin, 43401, 1914.	Modern Lighting Practice in the Clothing Industry.
Hogue and Dicker	Trans. I. E. S., 1914.	Factory Lighting.
Powell and Harrington	Trans. I. E. S., 1914.	Present Practice in the Use of Tungsten Filament Lamps for the Lighting of Metal Working Plants.
Durgin	Trans. Illg. Eng. Soc., 1918, p. 415.	Productive Lighting Intensities.
Harrison and Magdsick	Elec. World, June 21, 1919, p. 1319	Selecting Equipment for Industrial Lighting.
Simpson	Trans. Illg. Eng. Soc., 1915, p. 868.	Illumination and One Year's Accidents.
Harrison	Trans. Illg. Eng. Soc., 1917, p. 409.	Effective Lighting of Factories.
Simpson	Trans. Illg. Eng. Soc., 1918, p. 429.	Lighting Curtailment and Accidents.
Hogue and Kirk	Trans. Illg. Eng. Soc., 1920, p. 46.	Factory Lighting.
Store Lighting		
Ford	Bulletin No. 80, Univ. of Iowa, 1914.	Store Lighting.
Law and Marshall	Trans. I. E. S., 1911, p. 186.	The Lighting of a Large Store.
Law and Powell	Trans. I. E. S., 1912, p. 437.	Present Practice in Small Store Lighting with Tungsten Filament Lamps.
Law and Powell	Trans. I. E. S., 1913, p. 515.	Distinctive Store Lighting.
Edison Lamp Works, G. E. Co	Bulletin No. 43403, 1914.	Store Lighting with Mazda Lamps.
Edison Lamp Works, G. E. Co	Bulletin No. 43500, 1914.	Lighting of Large Stores.
Shalling	Trans. I. E. S., 1913, p. 17.	Department Store Lighting.
Cravath	Electrical World, 1909, p. 53.	The Illumination Design of a Clothing Store.

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249. Selected list of reference pertaining to illumination designs.—*Continued*

Author	Where published	Title
Residence Lighting		
Powell	Trans. I. E. S., 1914, p. 45.	Lighting a Simple Home.
Edwards	General Electric Review, March, 1919.	House Lighting.
Cassidy	Trans. Illg. Eng. Soc., 1915, p. 55.	Art and Science in Home Lighting.
Luckiesh	Elec. Review, Feb. 1, 1919.	Lighting of a Middle Class Home.
Office Lighting		
Aldrich and Malia	Trans. I. E. S., 1914, p. 103.	Indirect Illumination of the Offices of a Large Company.
Harrison	Elec. Review, 1918, p. 825 and 864.	Lighting of Offices and Drafting oms.
Powell	Elec. World, Feb. 15, 1919, p. 316.	Office Lighting.
Edwards and Harrison	Trans. Illg. Eng. Soc., 1914, p. 164.	Engineering Features of Office Building Lighting.
Dicker and Kirk	Trans. Illg. Eng. Soc., 1915, p. 659.	Lighting in Downtown Office Buildings.
Hibben	Trans. Illg. Eng. Soc., 1916, p. 976.	Economics of Office Building Lighting.
Durgin and Jackson	Trans. Illg. Eng. Soc., 1915, p. 690.	Lighting of an Office Building.
Scofield and Law	Trans. Illg. Eng. Soc., 1917, p. 205.	Office Lighting.
Street Lighting		
Harrison	Elec. World, Sept. 4, 1915, p. 521.	Cleveland Lantern.
Millar	Trans. A. I. E. E., 1915, p. 1429.	Effective Illumination of Streets.
Mahan and Butler	Elec. World, July 24, 1915, p. 180.	Ornamental Street Lighting.
Cravath	Elec. World, Sept. 1, 1917, p. 414.	Street Lighting for Small Cities.
	Elec. World, Sept. 8, 1917, p. 473.	
Harrison	Trans. Illg. Eng. Soc., Oct., 1917, p. 305.	Refractor and Diffusing Globe for Street Lighting.
Rose and Butler	General Electric Review, p. 430	Ornamental-U tilitarian Street Lighting Units.
Ryan	Elec. World, Sept. 2, 1916, p. 457.	San Francisco Lighting System.
Miscellaneous		
Powell	General Electric Review, March, 1914, p. 318.	Interior Illumination.
Parsons and Smith	U. S. Naval Medical Bulletin, Vol. IV, No. 3.	The Illumination of Study Rooms.
Marks	The Brickbuilder, 1913.	Lighting Public and Semi-public Buildings.
Nutting	Journal Franklin Inst., March, 1917.	Principles of Good Lighting.
Harrison	General Electric Review, July, 1918.	Fundamentals of Illumination Design.
Marks and Woodwell	Trans. Illg. Eng. Soc., 1914, p. 643.	Planning for Daylight and Sunlight in Buildings.

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leaned at regular intervals, hence a fixed charge should always be included or this service. Lamps which require frequent trimming are cleaned at the ame time, and the cost is included under the maintenance charge.

"The energy cost can usually be readily computed, but will, in the case of ome electric illuminants, depend upon the voltage of the circuit, since this letermines either the wattage or the power-factor. The effect of power-factor is seldom considered, although it governs the investment in generators, ransformers, and wiring, and, in a small degree, energy required. To the entral station or isolated plant, the volt-amperes required by a given lamp re perhaps as close a measure of the cost of service as the actual wattage onsumed. When the consumer is purchasing energy on a kilowatt-hour asis this factor, of course, is eliminated so far as he is concerned."

Principles of cost accounting in illumination may be laid down and with discriminating application may serve to yield correct cost values. So largely, owever, are costs in lighting dependent upon local conditions, and so greatly lo these conditions vary, that it is unsafe to apply in one installation cost lata obtained somewhere else, unless the differences in condition are first onsidered and allowance is made in the data for differences in such conditions. But little in the way of reliable impartial cost data has been published.

250. Cost of light in relation to other expenses. The total cost of artificial light as a part of the cost of living or as a part of the total cost of operation of a business enterprise is very small. In 1912 the Department of Commerce and Labor in a bulletin entitled "Retail Prices 1890 to 1911" shows that as an average of 2,567 workingmen's families in 1901, the average cost of lighting per annum was $8.15 out of a total cost of $768.54, or 1.06 per cent. expended in lighting. The report of the Commission of Labor for 1903, as presented at the 58th Congress, offers statistics compiled from the expenditures of 11,156 workingmen's families; these show that the cost of lighting in workingmen's homes averaged then 1.13 per cent. The average for any group, in a classification according to wages earned, was found not to depart from this value to any great extent.

251. Proportion of lighting costs to total operating costs. (1913)

Class of lighting installation	Approximate cost of artificial lighting in proportion to total operating costs
Small wage-earner's home—ratio of cost of lighting to total income	1 per cent.
Well-conducted large manufacturing establishments which are well lighted with modern illuminants—ratio of cost of artificial lighting to total cost of output exclusive of selling expenses	½ to ¼ of 1 per cent.
Large retail mercantile establishments—ratio of total lighting cost to total sales	Probably less than 1.0 per cent.
Small stores—ratio of total lighting cost to total sales	2 per cent.
Modern loft buildings	1 to 2 per cent.
Street lighting appropriations by municipalities are of the order of 60 cents to $1 per inhabitant per year.	

PHOTOMETRY

FUNDAMENTAL PRINCIPLES

252. Disappearance or discrimination photometers. Various photometers have been devised based upon determination of the threshold of vision. Some involve the discrimination of fine detail and are known as **visual-acuity photometers.** A well-known example is the "illuminometer"

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or reading distance instrument, which has been employed to some extent for street-lighting work. In this instrument the criterion is the maximum distance from the light source at which a given fine print may be read or the size of print which may be deciphered at a given distance from a light source. In another type the criterion is the perception of a given contrast, and may involve either the adjustment of the contrast for disappearance or the adjustment of the illumination for disappearance of contrast. An example of this is the "illuminometer" of Kennelly and Houston.* Still a third type of disappearance photometer has, as a criterion, the minimum perceptible flicker, and involves adjustment of the rate of flicker to determine disappearance or adjustment of the illumination to determine disappearance of flicker. These several types of photometers and others involving, in a modified form, the application of the same principles, are impracticable for measurement of illumination because, like any threshold or limen test apparatus, they are subject to errors which are ocular or mental in origin and are of an order so great as to make the instruments useless as photometers. These errors may be reduced by circumscribing the use of the instrument with precautions which limit the physiological variables. Even when the utmost precautions are taken, errors of the order of 25 per cent. are to be expected. It is sometimes asserted that discrimination photometers are to be looked to for the ultimate determination of illuminating value. This has not been demonstrated however. The true field for such apparatus and one in which their utility is considerable, is in the study of vision.

253. Physical laws underlying photometry. Regarded as a physical measurement, photometry rests upon the application of the law that light from a point source varies inversely as the square of the distance (Par. **200**) and that the illumination of a plane surface varies as the cosine of the angle of inclination to the incident ray (Par. **201**). These laws must be applied with discrimination and with strict regard for their practical limitations. The inverse-square law holds good only when the light source is relatively small with reference to the distance from the source to the illuminated surface. If the distance is less than five times the maximum dimension of the source, material divergence from the inverse-square law will result. The law may not hold good for relatively short distances when reflecting or refracting devices are employed to concentrate the light in a particular direction, as, for example, when a parabolic reflector is employed with an incandescent lamp or, as a more extreme example, a search-light. The cosine law applies to any plane surface insofar as the incident light is concerned. In many cases, however, the incident light is judged by the reflected or the refracted light. In such applications, the cosine law holds good only if the surface is a true diffusing surface, altogether free from regular reflection characteristics.

254. Ocular characteristics affecting photometry. In the comparison of lights of similar color, the process is not unlike other physical measurements since visual peculiarities do not affect the result. In heterochromatic photometry, in which lights of different colors are compared, ocular characteristics must be borne in mind, and the measurements must be carried out with due regard to the requirements which they impose. The three characteristics of greatest importance are as follows: (a) the Purkinje effect (Par. **255**); (b) yellow-spot vision (Par. **256**); (c) partial color blindness (Par. **257**).

255. The Purkinje effect is the name applied to the greater sensibility of the human eye to blue and green light at very low intensities than to red or yellow light. In accordance with this characteristic, if a mercury-vapor lamp is adjudged equal in illuminating power to a tungsten-filament lamp when the two are compared at a distance of 10 ft., the mercury-vapor lamp would be adjudged of higher illuminating power than the tungsten lamp if the comparison were to be made at a great distance.

256. Yellow-spot vision. The central portion of the retina of the eye, the yellow spot, comprehends a visual angle of 6 to 8 deg., throughout which the eye is less sensitive to green and blue light than is the surrounding portion of the retina. If a comparison of a mercury-vapor lamp and a tungsten lamp of equal power were to be made upon a surface so small as to

* *Electrical World*, March 9, 1895.

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fall within a visual angle of 6 deg., the mercury-vapor lamp would be adjudged of lower illuminating power than the tungsten. While a relatively higher evaluation would be accorded the mercury-vapor lamp if the illuminated surface were to be enlarged so as to comprehend a visual angle of say 24 deg.

257. Partial color blindness is often encountered. Eyes of certain individuals are found to be less sensitive to light of a given color than are normal eyes. The characteristic sensibility of the eye to light of different colors and of a given intensity when plotted diagrammatically is known as the luminosity curve* (Par. 10). If an observer's sensibility to red is low, as shown by the luminosity curve for his eye, he would, of course, adjudge the illuminating power of a mercury-vapor lamp to be relatively high as compared with that of a tungsten lamp.

258. Psychology in photometry. In all photometry and especially in heterochromatic photometry, observers whose eyes may have quite similar characteristics sometimes secure markedly different results, due to the fact that they form different concepts of the appearance which two illuminated surfaces must assume when they are balanced. Usually, an observer forms a concept and adheres to such concept until persuaded that it is improper. This is a matter of memory, tradition, and, sometimes, of external influence. It is common experience that observers who work together in photometry tend to form similar concepts and to agree in their observations under all conditions. Sometimes the concept agreed upon by such observers is the probable correct concept reached as a consensus of opinion. On the other hand it may be the concept of one observer which another observer has been influenced, unconsciously, to accept.

259. Heterochromatic photometry. No final determination of the relative illuminating power of lights of different colors has been made. It seems probable that there cannot be any one factor to express this relation because the illuminating power of light of different colors depends, first, upon the intensity at which it is employed and second, upon the purpose for which it is employed. Conditions are ripe, however, for the establishment of arbitrary standards of light of different colors to serve for purposes of heterochromatic photometry. Much work is being done on the subject and reliable standards representing the best assignments of values which have been made will shortly be available. With such standards, consisting either of sources yielding light of various colors or of color filters for modifying the light of a given source, heterochromatic photometry is reduced to the comparison of lights of similar colors, under which conditions the ocular characteristics affecting the problem may be largely ignored.

STANDARDS OF LUMINOUS INTENSITY

260. Primary standards now in use. All primary standards which are employed in practical photometry are flame standards. Flame standards are esteemed rather highly in the gas industry because their candle-power is considered to vary more or less as does the illuminating gas flame with changes in atmospheric conditions. Flame standards include the Hefner lamp, the Pentane lamp, the Carcel lamp and candles. All are capable of yielding accurate results when employed with strict regard for their limitations. The material of combustion must be carefully selected in accordance with strict specifications. The construction must be accurate; good ventilation and freedom from drafts is essential; accurate adjustments and corrections for variations from standard atmospheric conditions are fundamentally important. For detailed description see any text-book on photometry.

261. Proposed primary standards. The need for a primary standard of light which shall have a definite value and be absolutely reproducible has led to a number of interesting proposals. Without referring to a number of proposals which have been given a trial, without attaining sufficient sucess to warrant their adoption, it may be said that there are two recent proposals of considerable merit. Steinmetz† has suggested that the red, green and blue line radiation of the mercury arc, aggregating one watt, be adopted as a standard of light. Ives‡ has recommended one watt radiated in energy

* Ives. *Philosophical Magazine*, December, 1912.
† Transactions A. I. E. E., 1908, p. 1319.
‡ Transactions Illg. Eng. Soc., 1912, p. 376.

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of maximum luminosity. Both suggestions depend for successful application upon the accurate measurement of radiant energy, and Ives' suggestion involves further the accurate transfer from green to white light through heterochromatic photometry.

263. International candle and its equivalents. An important step toward international agreement upon a unit of light was taken through the cooperation of the Illuminating Engineering Society and the Bureau of Standards in 1909. While the Hefner lamp is the official unit of light in Germany, yet the simple relation 1 Hefner = 0.9 international candle was agreed upon as the result of the same international cooperation. The following relations now hold: 1 international candle = 1 Pentane candle = 1 Bougie decimale = 1.11 Hefner unit = 0.104 Carcel unit.

263. Representative standards. Seasoned incandescent lamps calibrated in international candles and held in the custody of the Government laboratories in England, France and the United States are for all practical purposes the official standards of light in these countries. Accurately calibrated lamps derived from these standards may be procured from the Bureau of Standards and from testing laboratories for use as reference standards.

264. Reference standards. It is customary in important photometric work to procure a number of reference standards calibrated in international candles and to use these occasionally for the verification of other standards which are in daily use and which are known as working standards. These in turn are used for the occasional calibration of comparison standards which are burned continuously in a photometer. All electric incandescent lamp standards have a limited life; hence lamps which are used for continuous comparison purposes must be verified occasionally and the repeated use of the working standards employed in such verifications in turn limits their period of constancy. A complete range of reference standards and working standards is important if comparison standards are to be relied upon for accuracy.

PHOTOMETERS AND PHOTOMETRIC APPARATUS

265. Physical or non-ocular photometers. In the measurement of radiant energy there are employed, at various times, the thermopile, the radiometer, and the bolometer. These are affected by radiation of various wave lengths in several characteristic ways, and, for some classes of physical investigation, have very important uses. The photo-electric cell, the selenium cell, and the photographic plate also have been investigated with a view to employment as substitutes for the eye in conjunction with a photometric device. In addition to characteristics which impose serious limitations to their use for practical work, these devices are open to the further objection that radiation within the visible spectrum does not affect them in the same proportions as it does the human eye. Their sensibility characteristics do not conform to the luminosity curve of the human eye. The photo-electric cell, for example, is most sensitive in the region of 0.44μ in the violet end of the spectrum; the selenium cell, on the other hand, is most sensitive to radiation in the region of 0.7μ, which is in the orange-red region of the spectrum. It is possible to correct these devices by employing color screens of such characteristics as to alter the sensibility curve to the desired extent. It is understood that those who are engaged in the study of these devices feel encouraged to hope that they may yet prove their value in some classes of photometric work. Up to the present time, however, they have been of scientific interest rather than of utility, in so far as ordinary photometry is concerned.

266. Photometric devices—ocular. It is a characteristic of the human eye, termed "**induction**" that a uniform dark surface placed next a lighter surface appears darker in the region immediately adjacent to the lighter surface than it does in the region farther removed. It follows that in bringing two surfaces to equivalent brightness, the contrast will appear more marked if the surfaces can be brought into close juxtaposition, and, if the contrast is more marked, equivalency can be established with greater accuracy. Utmost precision in such adjustments is attained if the surfaces are made continuous and without distinguishable separation. A photometric device (sometimes called a sight box) is an appliance for promoting

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the brightness equivalency adjustment which is the essence of photometry. The more usual types may be classified as comparison devices, contrast devices, and flicker devices.

267. Comparison devices. For a description of many simple photometric devices which are of historic interest, see text-books.* The comparison

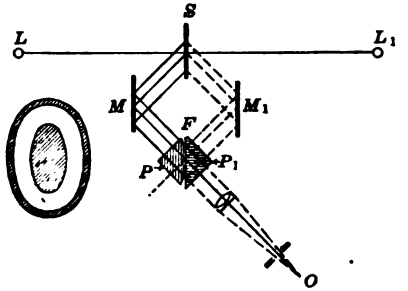


FIG. 55.—Lummer-Brodhun photometer, comparison type.

device in most general use at the present time is the simple Lummer-Brodhun cube, which is illustrated in Fig. 55. Light from lamp, L, falls upon one side of white plain surface, S, and is in part reflected through mirror, M, and that part of the two prisms, P and P_1, which are in optical contact, to the eye, O. Light from the other lamp, L_1, falls upon the other side of S, is reflected from the mirror, M_1, to the prism, P_1. That part of it which falls upon the part of the prism which is in optical contact with prism P, passes

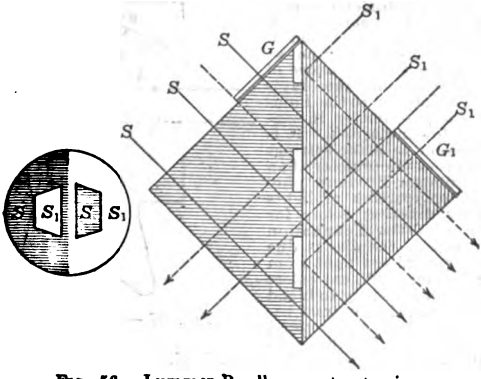


FIG. 56.—Lummer-Brodhun contrast prism.

through P and is absorbed, while that which falls upon the remainder of the hypothenuse face of P_1, is reflected to the eye O. Portions of the two surfaces of S are therefore brought into juxtaposition, as indicated in the diagram, and without perceptible line of separation. This form of photometric device is excellent where rapid settings are desired, but is not quite equal for precision work, to the Lummer-Brodhun contrast device.

* Especially "Illumination—Its Distribution and Measurement," Trotter.

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268. The Lummer-Brodhun contrast prism is employed in the same manner as the comparison prism illustrated in Fig. 55. Its construction is different, however, as illustrated by the plan in Fig. 56. The hypothenuse face of one prism is ground away in three places, as indicated, and the alternate halves of the outer faces of the two prisms are covered by thin glass plates, G and G_1, which absorb 7 or 8 per cent. of the light which passes through them. The photometric field appears as illustrated in Fig. 56, the light from one side of photometric surface S being represented on the left of the diagram and by the trapezoid located in the right half of the field, the being 7 or 8 per cent. less bright than the other half of the field. Similarly the light from the other photometric surface, S_1, is represented by the semicircle in the right of the figure and by the trapezoid in the left half of the figure, the latter again being 7 or 8 per cent. less bright. With the contrast cube in proper adjustment and of proper optical characteristics, a photometric balance should bring to equivalent brightness trapezoids, S and S_1, and also semicircle S and S_1; in addition, the contrast between trapezoid S_1 and semicircle S should equal the contrast between trapezoid S and semicircle S_1. Devices of this type have highest known sensibility for photometry where no considerable color difference is involved.

269. Bunsen contrast photometer. In the Bunsen photometer a translucent screen normal to the photometric axis is rendered of higher translucency at the centre, and the appearance of the opposite surfaces, when illuminated by the two lamps between which it is located, is observed through mirrors placed about 140 deg. from one another, as illustrated in Fig. 57. The greater translucency of the centre of the screen may be made by the application of hot paraffin, or, as in the Leeson disc, may be accomplished by cutting a round or star-shaped hole in the disc itself and pasting thin rice paper over both surfaces. Care and skill in the construction of the disc are essential to precision of operation. As in the Lummer-Brodhun contrast photometer, the Bunsen photometer presents to view two contrast fields. If properly constructed with mirrors of equal absorbing power, a condition of balance should bring equality of brightness and equality of contrast.

The Bunsen photometer is preferred by some for routine lamp testing where highest precision in individual measurements is not so important as good maintenance of accuracy throughout the day's work. It is inferior to the Lummer-Brodhun photometer in sensitiveness at low intensities. It is somewhat easier to make settings with the Bunsen photometer than with the Lummer-Brodhun photometer in comparison of lights of markedly different colors for the reason that the illumination of each surface of the disc is due in part to transmitted light from the other surface. Where colors differ, there is a tendency to blend and decrease the color contrast below the actual contrast encountered with a photometer like the Lummer-Brodhun, where the lights are not mixed.

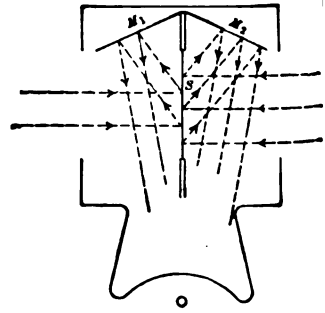


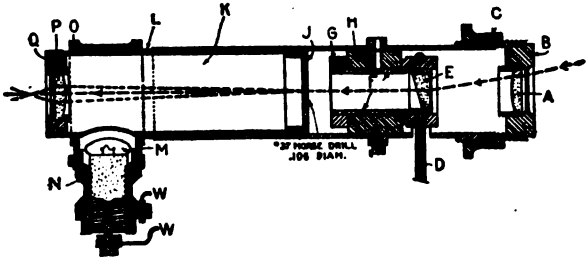
FIG. 57.—Bunsen photometer.

270. Flicker photometer. In flicker photometry the criterion of adjustment is the disappearance of the flicker effect, or rarely, the equality of two flicker effects. The flicker photometer is used as a rule only when lights of markedly different colors are to be compared. Due to persistence of vision, the colors, though markedly different, tend to blend when presented to the eye in rapid alternation, and the color differences cease to be perceptible, while differences in brightness of the two surfaces are still visible. It is thus possible to make comparisons of markedly different lights with much less difficulty than when the equality-of-brightness method is employed, and different observers are much more likely to secure similar results, because

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the criterion rests upon a physiological effect and leaves room for less difference of opinion or less variation of concept than does the equality-of-brightness method. Ives* has found that with the flicker photometer, blue and green light is adjudged of lower illuminating power when compared at low intensities with red and yellow light. This is a reversal of the Purkinje effect (Par. 255) which obtains in equality-of-brightness measurements at very low intensities. He concludes, as the result of his investigations, that the flicker photometer offers the best means of dealing with heterochromatic photometry, but its use should be limited by specifying a standard intensity at which comparison shall be made, a standard visual angle for the photometric field, and observers who are free from peculiarities of color vision. Incidentally, a similar prescription applied to any kind of photometry would do much toward standardization. Ultimately, heterochromatic photometry must be based upon the illuminating power as judged by some such criterion as equality of brightness or power to reveal detail. The disappearance of flicker cannot be considered as an ultimate criterion. However, a flicker photometer once verified and accepted in a given form as a reliable device for heterochromatic photometry, should prove very useful in that class of work because of the readiness with which settings can be made.

271. Forms of flicker photometer. Rood† devised the first flicker photometer, which consisted of a wedge, the two faces of which formed the photometric surfaces, which were viewed alternately through a revolving



Elevation of flicker attachment.

A, Front lens.	*J*. Front of eye-piece.
B. Collar for lens.	*K*. Eye-piece.
C. Collar to hold telescope rigid in head.	*L*. Collar on eye-piece.
D. Belt.	*N*. Lamp socket.
E. Rotating prism.	*O*. Rotating collar for lamp.
F. Rotator bearing.	*P*. Eye lens.
H. Stationary bearing for rotator.	*Q*. Collar for lens.
	W. Wires to lamp.

FIG. 58.—Kingsbury-Ives Flicker attachment for Lummer-Brodhun photometer head.

lens. The Whitman photometer is provided with a wheel, portions of whose rim are inclined in opposite directions. As the wheel revolves, it presents to the eye photometric surfaces illuminated in turn by each source under comparison. The Simmance-Abady photometer operates on a similar principle. The Schmidt and Haensch flicker photometer is a refinement of the original Rood photometer. Kingsbury‡ has devised a flicker attachment for a standard Lummer-Brodhun photometer head which is constructed in accordance with the principles of standardization suggested by Ives (Par. 270). This attachment is illustrated in Fig. 58.

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* *Philosophical Magazine*, November, 1912.
† Science, Vol. VII, p. 757.
‡ Kingsbury. *Jour. Frkln. Inst.*, 1915, p. 215.

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272. Means of changing intensity of light for photometric adjustment. The principal methods of adjustment of the intensity of illumination upon a photometric surface are variable distance, variable inclination of the surface, variable rotating sector disc, variable diaphragms, polarising devices.

273. Variable distance. This adjustment may be accomplished by moving the photometric device between fixed lamps; by fixing the photometric device and moving the comparison lamp; or by joining the photometric device with the comparison lamp and moving both as a unit. The first mentioned method is that ordinarily employed in commercial photometry of incandescent lamps. The moving comparison lamp is often used in portable photometers and in tests of lighting auxiliaries where it is desired to maintain a fixed distance between the photometer and the light source under test. The movement of the photometric device and the comparison lamp as a unit is sometimes employed in precision photometry where it is desirable to maintain a fixed intensity of illumination upon the photometric surface. In all applications of the variable-distance method of adjustment, it is necessary to keep in mind the limitations of the inverse-square law (Par. 253) and to guard carefully against errors due to light reaching the photometric surface after being reflected or refracted from other surfaces in such a manner as to interfere with adherence to the inverse-square law.

274. Variable rotating sector disc. Serious mechanical difficulties are encountered in constructing a rotating sector disc whose apertures may be varied precisely during rotation. Even if such a device is constructed successfully, it is inherently of low precision in the smaller aperture adjustments where a slight angular adjustment error may involve a large error in the total percentage of light transmitted. One of the interesting applications of this idea is embodied in the Beckstein photometer (Par. 284) in which the beam of light is rotated about the centre of a stationary sector disc whose angular openings are adjusted as desired.

275. Variable diaphragms. Unlike the variable-distance method and the variable rotating sector disc method, the variable diaphragm method is dependent exclusively upon empiric calibration. However, when used in conjunction with a uniformly bright surface, as a diffusing surface or lens, it is a very useful device, and capable of very accurate calibration. Its principal use in commercial photometry is in portable photometers.

276. Methods of employing photometric apparatus. The photometric devices which have been described may be used upon bars for the measurement of candle-power in one direction, or with integrating devices for the measurement of total flux, or in portable photometers. In all such applications, any of the methods of varying the intensity which have been described, may be employed. The principles are the same and the applications differ only in accordance with the dictates of convenience and practicability.

277. Photometer bars. In the measurement of horizontal candle-power and in the measurement of distribution of light about a source, it is customary to employ a track upon which carriages supporting lamps or photometric devices, may travel smoothly and easily. The **Reichsanstalt bar** is an approved type which, with various modifications, may be procured from any manufacturer of photometric appliances.

278. Light-distribution apparatus. A considerable variety of appliances for facilitating the determination of radial distribution of light is available. These appliances include the Dibdin photometer; devices employing respectively one mirror, two mirrors and three mirrors; the Matthews photometer, employing a ring of mirrors and apparatus in which the test plate is revolved about the source. For detailed description see text-books on photometry and manufacturers' catalogues. All such appliances are designed to facilitate the determination of the intensity of light at various angles in the vertical plane. Since the inverse-square law does not always apply strictly to light from reflectors at the short distances at which the light is utilized, it is good practice to maintain a fixed distance between the surfaces of the photometric device and the centre of the light source.

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INTEGRATING PHOTOMETERS

279. General description. An integrating photometer yields in a single measurement the value of the total flux of light or the mean spherical candle-power of a light source. In general, most such devices, by optical or mechanical means, reduce the intensity of the light, at various angles to the vertical of the light source, in proportion to the area of the zone which the angle bisects, and provide a summation of such reduced intensities for the several angles throughout the vertical plane of the source. The **integrating sphere** intercepts and provides an indication of the total light produced by the source. Perhaps the earliest integrating photometer was **Blondel's lumeter.*** Kennelly† also devised an apparatus for mechanical integration. The instruments of Matthews and Ulbricht, and especially the latter, which are used at the present time are described in text-books.

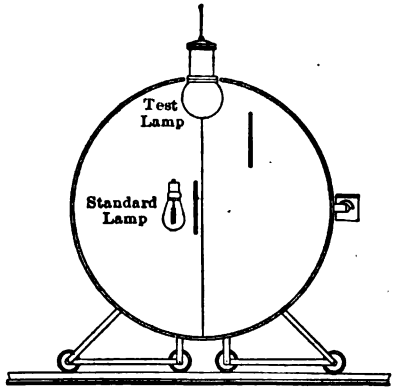


FIG. 59.—Integrating sphere for measuring total lumens or mean spherical candle-power.

280. Ulbricht integrating sphere. The integrating sphere devised by Ulbricht has been found to be the most accurate and practical form of integrating photometer It has been shown that if a light source be located within a hollow sphere having a diffusing inner surface and be screened from a given element of that surface, the illumination of such element, being due entirely to diffuse reflection, will be independent of the location of the light source and its distribution characteristic. In practice the Ulbricht photometer is a hollow sphere, usually 40 or 80 in. in diameter. It is equipped to facilitate the introduction of the light sources to be measured. It is provided with a suitable screen which is located between the light source and a window which forms one surface of the photometric device. The general arrangement of the sphere is indicated in Fig. 59. The integrating sphere is now recognized as the approved appliance for the determination of total light flux or mean spherical candle-power.

PORTABLE PHOTOMETERS

281. Test plates. As portable photometers are generally designed for the measurement of illumination intensities, they are equipped with test-plates which form one of the two photometric surfaces of which the brightnesses are compared. As such plates must receive light at all angles above the horizontal and from all directions, obedience to Lambert's cosine law (Par. **201**) is important, and the deviation of most surfaces which it is practicable to use from such law constitutes a material error. When the test-plate is translucent, and for photometric purposes is viewed from beneath, errors of this kind are irrespective of azimuth and are a function of the angle of incidence of the flux under test. When the test-plate is viewed from the side on which the test flux is incident, directional errors intrude and are in addition to those of inclination. Deviations from true value encountered in the measurement of light flux incident upon the test-plate at various angles

* Blondel. "La Determination de l'intensite moyenne spherique des sources de lumiere," *Comptes rendus*, March and April, 1895 and *L'Eclairage Electrique*.

† Houston and Kennelly. "Electric Incandescent Lighting," p. 461.

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are shown in the following table. In order to avoid these systematic or unsystematic errors to which most measurement of illumination is liable, a compensated form of either transmitting or reflecting test-plate has been devised* one form of which is illustrated in Fig. 60.

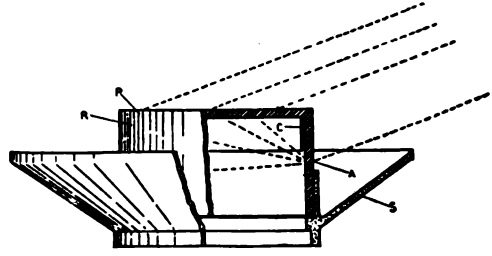


FIG. 60.—Compensated photometer test-plate.

In order to compensate for the deficiency in brightness under light incident at very acute angles, a part of such flux is brought to bear upon the lower surface of the test-plate, enhancing the brightness of the observed surface. The amount of this compensating flux is subject to adjustment and the test-plate can therefore be made as accurate as it is possible to measure its brightness. Comparison of measured deviations from the cosine law for two different uncompensated test-plates and for one compensated plate are shown in the following table:

Test-plate Errors

Angle of incidence, degrees	Deviation from true value		
	Plate A	Plate B	Plate A compensated
0	0.0	0.0	0.0
10	0.0	+ 0.5	0.0
20	0.0	+ 0.5	0.0
30	− 1.5	+ 0.5	+ 0.5
40	− 4.0	+ 0.5	+ 1.5
50	− 6.5	− 3.5	+ 1.0
60	−13.5	−11.0	+ 1.5
70	−15.0	−20.5	0.0
80	−48.0	−44.0	− 0.5
85	.....	−72.0	−11.0

282. Foot-candle meter.† This is an instrument without moving parts designed for the approximate determination of illumination intensities on any plane. It is of a character which makes it adaptable for the use of those not highly trained in photometry and serves satisfactorily for illumination measurements where high precision is not required.

283. European portable photometers. Perhaps the first carefully designed portable photometer to achieve distinction was the **Weber photometer.** While portable in form, this instrument is adapted to laboratory rather than to field work. The **Beckstein photometer** is of the semi-portable type and is more elaborated and complicated than the Weber photometer. It is perhaps more suitable for academic purposes than for practical photometry. Several *English* photometers have been designed, but as a rule these have been of a relatively crude character not capable of yielding sufficiently precise results to command much use in American practice.

* Sharp and Little. *Trans.* Illg. Eng. Soc., 1915, p. 727.
† Sharp. *Electrical World*, 1916, p. 569.

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284. Macbeth illuminometer. This instrument, of which the structural features are indicated in Fig. 61, is designed for the measurement of illumination intensities and brightness, combining reasonably high accuracy with a fair degree of portability. It is accompanied by a complete equipment for the supply, control and measurement of current for the operation of the comparison lamp and with a reference standard for recalibration.

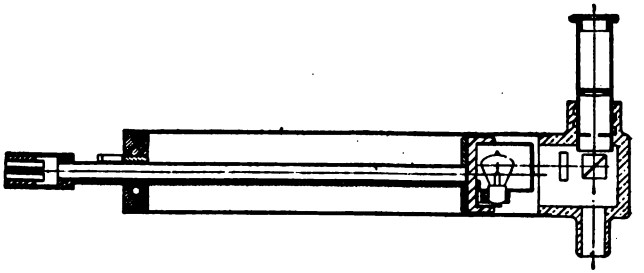


FIG. 61.—Macbeth illuminometer.

The scale of the illuminometer yields direct readings from 1 to 25 foot-candles, a range which is increased from about 0.02 to 1,200 foot-candles by the use of neutral glass absorbing screens. The optical device is a Lummer-Brodhun cube and the comparison lamp is designed to operate in conformity with the inverse square law according to which the scale is calibrated.

285. Sharp-Millar photometer. This is available in two sizes, respectively 12 and 24 in. long. Fig. 62 shows the essential features as embodied

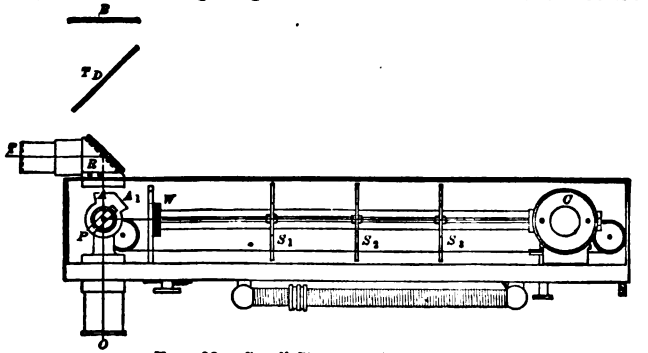


FIG. 62.—Small Sharp-Millar photometer.

in the smaller size. The photometric device *P*, consists of a Lummer-Brodhun cube or a microscope glass, mirrored except for a central aperture. Looking through this aperture from ocular aperture *O*, the observer sees either the attached test plate *T*, which is upon the end of a rotating tube, or the detached test plate *Td*. The photometric surface, as seen through this tube, is surrounded in the photometric field by a portion of translucent glass comparison window *W*. The illumination of window *W* varies inversely as the square of the distance to moving comparison lamp *C*. The value of a setting is indicated upon a direct-reading translucent scale, illuminated from within by the comparison lamp. A system of baffle screens, *S* − 1, etc., protect the window against stray light. The range of the instru-

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white when average daylight is received upon the colored glasses. Color sensation values are expressed in terms of such maxima. The colorimeter may be employed in the study of light from line spectrum sources, whereas the spectrophotometer is limited to the study of continuous spectrum or approximately continuous spectrum sources. Sensation values (Par. 27) may be shown with the aid of the Maxwell triangle, Fig. 64.

In this diagram, several illuminants are located as to color, and are shown in comparison with the theoretical black body at several temperatures. The sum of the expressions of color sensations is unity. The sum of the perpendicular distances from the three sides of an equilateral triangle is equal to

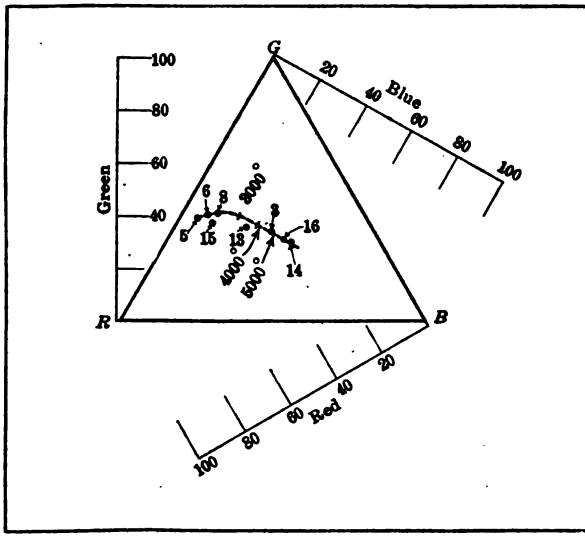


FIG. 64.—Color triangle. For key to numbers see Par. 27.

the altitude of the triangle, which also is taken as unity. Hence, the three color sensations for any illuminant may be indicated by a point on the triangle. The dotted line represents the color of the black body at several temperatures.

PHOTOMETRIC ADJUNCTS

288. Standardizing equipments. An adequate supply of reference standard lamps is important. As far as practicable, these should be of the same types and sizes as the lamps to be tested. For use with a portable photometer there should be a standard lamp box, in which the lamp is enclosed and in which, preferably, there is some device for facilitating the establishment of a standard distance between the lamp and the photometer.

289. Photometer scales. In practical photometry, the desirability of having all photometers direct-reading will be obvious. In the case of a fixed photometric device and a moving comparison lamp, the scale is computed in accordance with the simple application of the inverse-square law. A fundamental distance is established at which a given light intensity will be indicated. Distances for other intensities are obtained by the simple application of the inverse-square law, thus:

$$\frac{I}{I_1} = \left(\frac{d_1}{d}\right)^2 \qquad (17)$$

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In the case of a fixed distance between the test and comparison lamps and a photometric device moving between them, the midway point is assigned the value at which it is desired to maintain the comparison lamp. All other points are determined in accordance with the following equation:

$$d = \frac{D}{\sqrt{\frac{I_c}{I_t}} + 1} \qquad (14$$

where d is the distance between the test lamp and the photometric device, D is the distance between lamps, I_c is candle-power of the comparison lamp and I_t is the candle-power of the test lamp.

290. Color filters. Where light sources of a variety of types are to be tested, it is desirable to have an adequate range of color filters which will tend to eliminate most of the problems of heterochromatic photometry. These should have authoritative calibration. Both glass and liquid-solution color filters are being developed on comprehensive scales.

291. Required accuracy in electrical instruments. Too much care cannot be devoted to the electrical measuring instruments employed in photometry. To emphasize this it is necessary only to repeat that with Mazda lamps the candle-power error involved in a 1-per cent. voltage error is 6 per cent., and that the corresponding error due to a 1-per cent. ampere error is 6 per cent. Practically all portable voltmeters and ammeters have appreciable scale errors. The extent of such errors should be determined by securing calibration curves for the instruments, and corrections should be made accordingly. Some instruments have temperature coefficients which introduce material errors at times. Also some voltmeters and ammeters are influenced appreciably by external fields. All the precautions taken in electrical measurement should be applied in the use of electrical instruments for photometric work.

292. Rotating sector discs. In most laboratory photometry it has been found desirable to use a number of sector discs which are interchangeable on the rotating shaft and which have fixed angular openings, yielding transmission coefficients of respectively 0.1, 0.01, etc. Such employment of the rotating sector disc promotes ultimate accuracy, since, if adjustable discs are used, the opportunity for undetected adjustment errors is considerable, and the adjustment accuracy is low with small angular openings.

293. Absorbing screens form a valuable adjunct to photometric equipment. Their transmission coefficient, however, is not accurately controllable, and a simple decimal value is therefore rarely obtained. Absorbing screens should transmit without diffusion, and should be free from serious selective absorption. Unfortunately, the usual absorbing screens having low coefficients of transmission, have considerable selective absorption.

294. Baffle screens. In practically all photometry it is essential to guard the photometric device against stray light. Opaque screens having suitably proportioned apertures are largely employed for this purpose. A series of these screens, painted black (for most precise work they may be covered with black velvet), is used, for example, on a photometer bar. Where the photometric device or the comparison lamp travels along a track, these screens must be re-located as occasion requires. A most satisfactory method is to so install them that they will be adjusted automatically to the movement of the lamp or photometer carriage. This may be accomplished by mounting them upon lazy tongs, as in several types of commercial lamp-testing photometers, or allowing them to slide upon the track, being pushed in front of the lamp as it approaches the photometric device, and drawn after the lamp by cords or otherwise as it recedes, as in the Sharp-Millar photometer. An alternative to the use of baffle screens is the employment of black velvet to cover all surfaces which may possibly reflect stray light to the photometric device.

295. Rheostats. The easy fine adjustment of the current or voltage of a lamp is important to precise work in photometry. Too much care cannot be expended in providing thoroughly satisfactory rheostats for this purpose. Step rheostats are unsatisfactory unless the steps are of such low resistance in relation to the magnitude of the current, that the change per step is extremely small. A helix of resistance wire, with the coils well insulated

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wound upon an insulated tube and mounting a sliding collar having a multiplicity of contact points, is the most generally acceptable form of rheostat for photometric work.

296. Lamp rotators. It is usually desired to obtain mean angular intensity of light rather than the light in some particular direction at a given angle. Wherever the nature of the illuminant permits, it is desirable, therefore, to rotate the light source during test, allowing the eye to integrate the intensities to obtain a mean. Most forms of illuminants can be rotated. The speed of rotation of course depends upon the extent to which the light distribution is asymmetrical. If the distribution is approximately symmetrical, a low speed of rotation will suffice. This being the case, it has been found practicable to rotate almost all types of illuminants, including most arc lamps and some forms of gas lamps. The lamp rotator therefcre becomes a valuable adjunct in a photometric laboratory. It must be good both mechanically and electrically. As the moving electrical contact required for the supply of the lamp may involve some potential drop, it is customary in the best construction to provide auxiliary moving contacts either of the brush type or of the mercury-cup type, in order to allow the measurement of voltage immediately at the lamp terminals.

PHOTOMETRIC TESTING

297. The substitution method of photometry consists in calibrating a photometer by means of a standard lamp of as nearly as possible the same characteristics as the lamps to be tested, and substituting the lamp to be tested for the standard lamp. A skilled photometrist employing a photometer of exact construction which is perfectly screened and is used with correct electrical instruments for determining the electrical conditions of circuits which are free from potential drop, may obtain correct results in the practical comparison of a test lamp against a standard lamp. Whatever the methods employed, every care should be exercised to secure these favorable conditions for photometry, but if, in spite of care, some conditions exist which are not exactly as they should be, it is quite possible that the substitution method may result in cancelling the effect of such conditions and avoiding erroneous results. By using standard lamps of the same size and type as the lamp to be tested, the substitution method results in correcting both errors of illumination and errors of electrical measurement. If stray light from a 100-candle-power lamp adds 5 per cent. to the illumination of a photometric surface when a moving photometric device is set at 100 on a scale, it will have the same effect when a standard lamp of the same size is used. If then a comparison lamp be calibrated for temporary use by means of the 100-candle-power standard lamp, it will be adjusted 5 per cent. too high. When the 100-candle-power test lamp is measured, the light of the comparison lamp against which it is balanced and the light from the test lamp will both be 5 per cent. too high. The result will be a correct setting. If a voltmeter be employed which has an error of 1 per cent., the effect of the error will be cancelled in the same way if the substitution method is followed. Where considerable photometric work is to be done, the provision of an ample range of reference standard lamps, in order to permit the extensive application of the substitution method, is true economy.

298. Good practice in measuring illumination. It is well to be provided with reference standard lamps and a box equipped with baffle screens or black velvet to prevent stray light, in order to produce illumination of known intensities from the standard lamp upon the photometer test plate. It is well to have sufficient standardizing equipment of this kind to permit of the verification of the photometer scale at a few points throughout its range and also the verification of photometer absorbing screens. The same equipment may be used in verifying the brightness calibration of the photometer, provided a standard surface of known qualities is obtained with the standard lamps. In such calibration, light of a known intensity is thrown upon the standard surface and the corresponding brightness of the surface is computed (Par. **206**), employing its coefficient of diffuse reflection.

In some illumination work it is sufficient to measure the intensity of illumination at certain points in a room, and it is usually sufficient to measure the brightness of certain objects in the room, as far as data on brightness are concerned. More frequently, however, it is desired to know the average maximum and minimum illumination intensities on certain planes, and

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derive the coefficient of utilization (Par. 188). In such instances it is c tomary to divide the plane of reference into rectangles, usually providing to 30 such rectangles for the room, or for each bay in the room. A det mination of the illumination intensity is then made at the centre of each r rectangle. The mean of such values is usually a fair approximation of average intensity for the entire plane. Where a detached test plate is e ployed in the measurement of illumination on a horizontal plane or at given angle of inclination to the horizontal, it is often desirable to employ automatic-leveling test plate. In the measurement of horizontal illumi tion in interiors, a plane 30 or 36 in. above the floor is usually selected. complete study of a room used, for example, for office purposes, sho include the average horizontal illumination on such a plane; the uniform of such illumination intensities; the brightness of the walls, light sources other especially prominent objects within view; and measurements of ei illumination intensities or brightness on desks to show depth and natur shadows encountered.

299. Precautions for avoidance of error. The following suggesti are commended by experience, and, if followed, are likely to result in avoidance of some of the most common errors.

Reduce color differences by the use of authoritatively calibrated c filters (Par. 290).

Follow the substitution method (Par. 297) as closely as practica Provide reference or working-standard lamps of the same size and type as lamps to be tested.

Consult the characteristics of the light source under test and adapt p tice accordingly. For example, allow an arc lamp or a large series incan cent lamp to burn for a short period in order to attain working temper before making measurements. In testing arc lamps whose values through a cycle corresponding with the feeding period, make certain results are average for such period.

Verify photometer-scale calibration by tests of standard lamps.

Repeat verification at reasonable intervals even though photometer has been used in interim.

Verify indications of electrical instruments used.

Observe strict cleanliness of apparatus. Dust on transmitting gl increases coefficient of absorption. Dust on black velvet reflects light.

Verify a few test results by tests upon other apparatus. It is relati simple for an observer to repeat settings with a given photometer. M certain that such settings are in accord with results determined by o employing different equipment.

In tests of reflectors make certain that the light source is strictly in accor with the manufacturer's standard of construction, both as to type a dimensions.

Assure correct location of the reflector with reference to the light sourc Slight variation in any of these conditions may affect the result materially.

In tests for candle-power and in light-distribution tests, look along th photometric axis from the position of the photometric device to the te lamp and to the comparison lamp. Make certain that all of the lig emanating from the light sources in the direction of the photometric devi reaches the photometric surface. Make certain that no other light reach the surface, that is, avoid stray light.

300. Sampling. In sampling for test purposes, whether the samples lamps, lighting auxiliaries, or illumination installations, it is important th the samples be unquestionably representative of the product which is to judged by the results of the test. It is also essential that the samples sufficient in number to guard against the exertion of undue influence upon t final result due to the presence of an eccentric individual among the sample It is hardly possible to judge intelligently in these matters unless one thoroughly acquainted with the characteristics of the product which is bei sampled. No small part of expertness in testing lies in the successful sa pling of the product to be tested. Lamps, reflectors, etc., are not unifor and very misleading results may follow upon injudicious sampling.

301. Principles of comparison. In comparing illuminants it is impo tant to bear in mind first, that some illuminants require more adaptation a suffer in efficiency more in adaptation for a given service than do other illum nants; and, second, that some illuminants deteriorate more largely in ef

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ciency during life than do others. For example, a magnetite arc lamp as equipped is well adapted to street-lighting service, and its efficiency in the condition delivered by the manufacturer is substantially its service efficiency. On the other hand, incandescent lamps may have to be equipped with globe or reflectors or both before application to street-lighting service, and their efficiency as shipped by the manufacturer is materially higher than is their service efficiency. As another example, the candle-power depreciation of a 25-watt Mazda lamp is less during its life than is the candle-power depreciation of a 100-watt Mazda lamp. Conclusions based upon initial laboratory values should be modified where necessary before determining upon relative merit of two different kinds or sizes of illuminants for a given class of service. Likewise, lighting auxiliaries are not always directly comparable on the basis of their initial laboratory values. The deterioration of reflecting surfaces may be rapid. Some surfaces collect and retain dust more largely than do others, and, in consequence, their deterioration of light is greater in a given period.

302. Discussion of results. In discussion of test results it is rarely possible to draw unqualified conclusions as to relative merit between appliances or installations which are of more or less the same order of merit. In any test all that is demonstrated is that a sample or a set of samples or an installation has been found, in a given instance, to be superior in certain respects. It is dangerous to draw sweeping conclusions from tests. To do so may mislead when test data are applied to appliances or installations which have not actually been tested. In discussing results of tests and drawing conclusions from tests it is well to be cautious in accepting the basis of measurement as a final indication of value. The candle-power of an incandescent lamp is one direction or in one plane is not necessarily an indication of the illuminating power of the lamp. In the long run, the total light flux or the mean spherical candle-power is most nearly a correct indication, but even this measurement may fail to indicate the real value of an illuminant for a certain class of service. It may be shown that the minimum normal illumination intensities provided by two installations of illuminants for street-lighting service are equal, but this does not demonstrate that the two systems are of equal value. One may deliver twice as much light as the other upon the street. The mean horizontal illumination may be in the long run a reasonably good measure of street-lighting effectiveness, but even this measure may fail to indicate the facts for certain classes of service. In short, tests of illumination should be conducted and conclusions should be drawn from such tests in accordance with the dictates of common sense and good engineering practice.

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SECTION 15

INDUSTRIAL MOTOR APPLICATIONS

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SECTION 15

INDUSTRIAL MOTOR APPLICATIONS
MACHINE TOOLS

BY LEON P. ALFORD

Former Editor American Machinist; Member, American Society of Mechanical Engineers

1. Definition. The term "machine tools" cannot be accurately defined. Broadly they are machines used to work and shape metals. A legal definition taken from the Underwood tariff law, Par. 167, reads as follows: "Machine tool as used in this paragraph shall be held to mean any machine operated by other than hand power which employs a tool working on metal."

2. The two principal classes into which they divide are distinguished by the kind of motion of the work or cutting tools. This motion may be either rotating or reciprocating. In the former instance the speed is usually constant throughout each operation, and the energy absorbed is used in overcoming the friction of the machine and in doing useful work in cutting or forming metals. The exceptions are machines that accelerate during the cutting operations, such as squaring-up lathes and lathe-type cutting-off machines. In the second class the power is subject to great fluctuations during a working cycle. For, in addition to the friction losses and useful work done there are large, regular demands for energy with which to retard and accelerate heavy parts of the machine, or the pieces which are being shaped.

3. The friction losses in rotating machines, such as lathes, boring mills, drilling machines, milling machines, grinders, and the like vary almost directly as the speed, the gear ratio remaining constant. The loss in the gearing and feeding mechanism comprises the larger part of the friction losses.

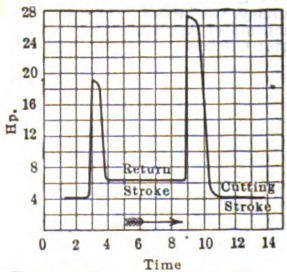


FIG. 1.—Power curve of a 60 by 60-in. planer.

4. The friction losses in reciprocating machines, such as planers, shapers, slotters, and the like, are very small in comparison with the losses due to inertia. In fact the inertia losses often exceed the useful work to such an extent as to determine the size of motor (this is especially the case with short-stroke machines). Fig. 1 shows a power curve taken by G. M. Campbell for a 60 × 60 in. × 20 ft. Pond planer. It shows the power input when running light plotted with time. The cutting-stroke speed was 25 ft. per min. (7.6 m. per min.) and the return-stroke speed 60 ft. per min. (18.3 m. per min.).

5. Group drive and individual drive. Motor applications to machine tools divide into two classes, group drives and individual drives. It is impossible to lay down a general principle to be followed in the selection of drive for a given case, for there are many modifying factors. Very large machines (those located under a crane) and all machines requiring variable-speed drive are commonly provided with individual motors. Small and medium-sized machines are usually arranged in groups and driven from a line shaft which in turn is driven by a constant-speed motor. If there are a number of reciprocating machines in the group it is not uncommon to add a fly-wheel to the motor.

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6. A comparison of lineshaft and individual-motor drives,* for machine tools is given in the following table:

Item	Lineshaft drive	Individual motor drive	Advantage of individual motor
1. Power consumption.	Constant friction loss in shaft, belts and motor, power for cutting.	Friction loss (motor and tool only) useful power only while working.	Less power required.
2. Speed control.	No. speeds = No. cone pulleys × No. gear ratios.	No. speeds = No. controller points × No. gear ratios.	More speeds possible; time saved in speed adjustments.
3. Reversing.	Clutch and crossed belt.	Reversible controller.	Time saved in reversing.
4. Adjusting tool and work.	Stopping at any definite point very difficult.	Can be started in either direction and stopped at any point.	Time saved in setting up and lining up.
5. Speed adjustment.	Large speed increments between pulley steps.	Small speed increments between controller steps.	Time saved by obtaining proper cutting speed.
6. Size of cut.	Limited by slipping belt; large belts hard to shift.	Limited by strength of tool and size of motor.	Time saved by taking heavier cuts.
7. Time to complete a job.	.....	.....	Much less time required as indicated for previous items.
8. Liability to accidents.	Slipping or breaking belt; injury to machine tools, cutting tool or prime mover.	Injury to machine tool, cutting tool or motor.	Much less liability to accident.
9. Checking economy of operations.	Close supervision required, very difficult to locate causes of delay.	Accurate tests possible by means of graphic meter which records automatically all delays and rate of cutting.	Causes of delay and remedies easily located without personal supervision.
10. Flexibility of location.	Location determined by shafting, and changes difficult.	Location determined by sequence of operation changes readily made.	Greater convenience in handling and increased economy of operation; more compact arrangement possible.

7. Motors for individual drives have been tentatively standardized by a committee of the National Machine Tool Builder's Association conferring with a committee of the American Association of Electric Motor Manufacturers. Although the design data were agreed upon in substance early in 1910, the motor manufacturers have failed to use it in the manufacture of their product. An abstract of the report of these committees appears in Par. 8.

* Robbins, Charles. *Trans.* A. S. M. E., Vol. XXXII, page 182.

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8. Standardized specifications for individual-drive motors.

(a) **Horse power.** Ten sizes are considered necessary for practically all requirements of electric drive for machine tools. These sizes are as follows: 1, 1.5 (for direct current only), 2, 3, 5, 7.5, 10, 15, 20 and 25.

(b) **Voltages** for direct-current motors should be 115 and 230 volts. For alternating-current motors the voltages should be 110 and 220 volts.

(c) **Horse-power ratings.** Where approximately standard load conditions exist, motors are to be given a continuous constant horse-power rating. For variable-speed motors used under intermittent service conditions, the standard 2-hr. continuous-duty rating is to be used for ordinary shop conditions.

(d) **Direct-current motor speeds.** Variable-speed motors are to be standardized for two ranges, namely, 2 to 1, and 3 to 1. The following table includes the recommended speeds for variable-speed direct-current motors:

Horse power	Speeds Ratio 2 : 1	Speeds Ratio 3 : 1
	r.p.m.	r.p.m.
1	1,500–750	1,500–500
1½	1,500–750	1,500–500
2	1,500–750	1,500–500
3	1,500–750	1,500–500
5	1,200–600	1,200–400
7½	1,200–600	1,200–400
10	1,200–600	1,200–400
15	1,200–600	1,200–400
20	900–450	900–300
25	900–450	900–300

(e) **Alternating-current motor speeds.** The following table gives the recommended speeds for polyphase 60-cycle alternating-current motors:

Horse power	Speeds	Horse power	Speeds
1	1,800 and 1,200	10	1,200 and 600
2	1,200	15	900 and 600
3	1,200	20	900 and 600
5	1,200	25	900 and 600
7½	1,200 and 900		

(f) **Frequency.** In considering constant-speed alternating-current motors 60 cycles is to be used as the basis.

9. Methods of applying motors to machine tools.*

(a) **Bench lathes** should be driven from a countershaft attached to the bench and driven in its turn by motor. Any type of motor may be used except the series-wound or the heavily compounded motors. It is essential to locate the machine in the most advantageous manner without regard to the position of the shaft.

(b) **Speed lathes** should be driven from a self-supported countershaft or by a direct-connected motor. In the latter case a variable-speed machine is to be preferred.

(c) **Engine lathes.** For these both variable-speed and constant-speed motors are used although engine lathes are usually group-driven. Where individual motors are used, each is placed on a bracket attached to the lathe and connected to it with a geared or chain drive.

(d) **Heavy engine lathes, forging lathes, etc.,** should be driven by direct-connected direct-current motors. The position of the motor should be low to reduce vibrations in its support. The output of these lathes may be increased from 20 to 25 per cent. by motor drive.

* DeLeeuw, A. L. *Trans.* A. S. M. E., Vol. XXXII, page 137.

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(e) **Axle lathes, wheel lathes and driving-wheel lathes** should be driven by direct-current motors.

(f) **Chucking lathes** usually are not motor-driven. If motors are used they should be of variable speed.

(g) **Automatic screw machines** in small sizes should be group-driven; in the larger sizes they should preferably be driven by variable-speed motors.

(h) **Sensitive drilling machines** in general should not be motor-driven. However, if machine is placed in an isolated location, a motor may be directly applied to the machine itself or the machine may be driven through a countershaft, from a motor on the floor.

(i) **Vertical and radial drilling machines** are usually group-driven unless they are isolated. If such machines are motor-driven, the variable-speed type should be selected. The motor may be direct connected to the machine itself or set up to drive the machine countershaft.

(j) **Boring machines,** if used for specialised work, are preferably belt-driven. If used for a variety of operations, a variable-speed motor is desirable.

(k) **Grinders** should be driven by constant-speed motors belted to the grinder countershafts.

(l) **Planers,** particularly those of small size, if located under a crane, should be driven by variable-speed motors. A recent development is the reversing-motor planer drive which is now being extensively tested, and promises to prove successful.

(m) **Shapers, slotters, etc.,** should usually be group-driven.

(n) **Knee and column-type milling machines** in the large sizes should be driven by variable-speed motors, especially if used in "gang" operations.

(o) **Planer-type milling machines** should be motor driven. Either the constant-speed or the variable-speed types will prove satisfactory.

10. Values of horse power required to cut metal*

Lathe-type tools

Material	Horse power required to remove 1 cu. in. per min.
Brass and similar alloys	0.2 to 0.3
Cast iron	0.3 to 0.5
Wrought iron	0.6
Mild steel (0.30–0.40 per cent. carbon)	
Hard steel (0.50 per cent. carbon)	1.00 to 1.25
Very hard tire steel	1.5

Drills

Material	Horse power required to remove 1 cu. in. per min.
Brass and similar alloys	0.4 to 0.6
Cast iron	0.6 to 1.0
Wrought iron	1.2
Mild steel (0.30–0.40 per cent. carbon)	
Hard steel (0.50 per cent. carbon)	2.0 to 2.5
Very hard tire steel	3.0

11. Determination of horse power required for machines under group drive. A table of power values for machine tools is given in Par. 12. These values are the result of tests made by the author under actual shop conditions, and apply to small and medium-sized machines only. The output of the factory where the investigation was made was light automatic machines. The parts operated on during the tests were iron and steel castings, drop forgings and bar stock. Manufacturing conditions were highly developed, and the degree of finish allowed was small. Because of these conditions the power values are still useful although they were obtained before the common use of high-speed steel in cutting tools. The values

* Robbins, Charles. *Trans.* A. S. M. E., Vol. XXXII, pp. 199 to 209

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have been checked by their application to a number of factories whose tot power load was known. This showed that, for a group of machines, the su of the power values given in the table is about 20 per cent. higher than th average working load. This is because of the intermittent service of too for various reasons, or the departmental slip.

12. Power machine tools in groups (see Par. 11)

Kind	Size	Observed horse power; maximum	Observed horse power; average
Boring Machines:			
Bullard, single head	36 in.	0.78	0.52
Bullard, double head	42 in.	1.72	1.08
Cam Cutters:			
Brainard	No. 2	.....	0.67
Brainard	No. 4	0.48	0.32
Brainard	No. 5	0.48	0.32
Lathe type, single head	.....	.....	0.32
Lathe type, double head	.....	.....	0.50
Cutting-off Machines.			
Hurlbut-Rogers	1⅛ in.	.....	0.12
Hurlbut-Rogers	2 in.	0.28	0.14 to 0.1
Hurlbut-Rogers	3 in.	0.34	0.20 to 0.2
Drilling Machines:			
Prentice Bros. radial	No. 0	.....	0.72
Prentice Bros. radial	No. 1	3.18	1.12
Woodward & Rogers	Sensitive single-spindle	.....	0.31
Dwight-Slate	2-spindle	.....	0.32
Woodward & Rogers	Sensitive 3-spindle	.....	0.35
Woodward & Rogers	4-spindle	.....	0.48
Woodward & Rogers	6-spindle	.....	0.71
Prentice upright	16 in.	.....	0.25
Prentice upright	18 in.	.....	0.35
Prentice upright	20 in.	.....	0.42
Prentice upright	22 in.	.....	0.59
Blaisdell upright	24 in.	.....	0.47
Blaisdell upright	26 in.	.....	0.22
Blaisdell upright	28 in.	.....	0.25
Blaisdell upright	30 in.	.....	0.30
Blaisdell upright	34 in.	.....	0.45
Blaisdell upright	36 in.	.....	0.53
Blaisdell upright	46 in.	.....	0.63
Blaisdell upright	50 in.	.....	0.83
Gear Cutters:			
Brainard	No. 4½	.....	0.15 to 0.3
Gould & Eberhardt	No. 3	.....	0.20
Brown & Sharpe	No. 3	.....	0.20
Grinders:			
Brown & Sharpe cutter and reamer grinder	No. 3	.....	0.32
C. H. Besly & Co. Gardner grinder	No. 4	1.42	0.53
Brown & Sharpe plain	No. 11	.....	0.80
Brown & Sharpe surface	No. 2	.....	0.40
Brown & Sharpe surface	No. 3	.....	0.50
Brown & Sharpe universal	No. 1	.....	0.60
Brown & Sharpe universal	No. 2	.....	0.76
Diamond wet tool grinder	.....	3.29	0.97*
Leland & Faulconer wet grinder	.....	.....	0.41 to 0.8

* Carrying 1 20-in. wheel. † Carrying 2 24-in. wheels.

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12. Power machine tools in groups.—*Continued*

Kind	Size	Observed horse power; maximum	Observed horse power; average
Drop Hammers:			
Biondell	40 lb.	.....	0.10
Pratt & Whitney	250 lb.	.....	2.00
Pratt & Whitney	400 lb.	.....	2.50
Pratt & Whitney	600 lb.	.....	3.00
Pratt & Whitney	800 lb.	.....	3.50
Pratt & Whitney	1,000 lb.	.....	4.00
Billings & Spencer	1,500 lb.	.....	5.00
Power Hammers:			
Bradley	100 lb.	.....	1.50
Bradley	150 lb.	.....	1.75
Keyseater:			
Baker Bros.	No. 4.	0.64	0.28 to 0.32
Lathes:			
Reed boring lathe	20 in.	.....	0.35
Reed boring lathe	30 in.	.....	0.41
Reed engine lathe	12 in.	.....	0.24
Reed lathe	14 in.	0.48	0.26
Prentice	16 in.	.....	0.34
Reed	16 in.	0.48	0.36
Blaisdell	18 in.	.....	0.39
Blaisdell	20 in.	.....	0.44
Reed	22 in.	0.37	0.32
Reed	24 in.	.....	0.25
Blaisdell	24 in.	.....	0.31
Prentice	28 in.	.....	0.31
Draper	38 in.	.....	0.58
Reed speed lathe	10 in.	.....	0.10
Reed speed lathe	14 in.	.....	0.12
Putnam squaring-up lathe	15 in.	.....	0.25
Gisholt turret lathe	Size H.	.....	0.70
Potter & Johnston semi-automatic	No. 1.	1.63	0.33 to 0.63
Jones & Lamson flat turret	2×24 in.	1.97	1.20 to 1.80
Milling Machines:			
Brainard	No. 1	0.47	0.30
Brainard	No. 3	0.64	0.26
Brainard	No. 4	.....	0.19 to 0.29
Brainard	No. 4½	.....	0.13 to 0.19
Brainard	No. 6	.....	0.26
Brainard	No. 7	.....	0.83
Brainard	No. 14	.....	0.25
Brainard	No. 15	.....	0.25
Becker vertical	No. 3	.....	0.26
Becker vertical	No. 5	.....	0.55
Becker-Brainard	No. 3	.....	0.17 to 0.25
Brown & Sharpe	No. 1	.....	0.15
Brown & Sharpe	No. 2	.....	0.25
Brown & Sharpe	No. 5	.....	0.30
Reed	No. 7	.....	0.83
Pratt & Whitney hand	No. 1½	.....	0.20
Planers:			
Whitcomb	17 in.	2.01	1.00 to 0.43
Whitcomb	22 in. × 5 ft.	2.34	1.16 to 0.53
Putnam	22 in. × 5 ft.	1.44	0.70
Putnam	24 in. × 6 ft.	.....	0.84
Putnam	26 in. × 5 ft.	1.59	0.81
Putnam	30 in. × 6 ft.	4.91	1.31
Putnam	30 in. × 8 ft.	5.46	1.56
Powell	36 in. × 10 ft.	4.00	1.60
Pond	50 in. × 9 ft.	2.94	1.14

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13. Power machine tools in groups.—*Continued*

Kind	Size	Observed horse power; maximum	Observed horse power; average
Polishing Stands:			
Brown & Sharpe	No. 3	.....	1.00
Diamond	No. 5	.....	1.19
Punch Presses:			
Bliss	No. 3	2.59	1.26
Profiling Machines:			
Garvin	No. 1	.....	0.50
Pratt & Whitney	No. 6	.....	0.40
Hack Saw:			
.....	12 in. to 14 in.	.....	0.06
Screw Machines:			
Brown & Sharpe automatic	No. 1	.....	0.60
Pratt & Whitney automatic	No. 2	.....	0.37
Pratt & Whitney	No. 2	.....	0.72
Pratt & Whitney	No. 3	.....	0.80
Brown & Sharpe automatic	No. 3	.....	0.80
Pratt & Whitney automatic	No. 3-O	1.04	0.90
Pratt & Whitney	No. 3-B	1.04	0.90
Brown & Sharpe	No. 00	.....	0.30
Cleveland	¾ in.	.....	0.40
Cleveland	2 in.	.....	0.87
Cleveland	2½ in.	1.04	0.90
Pratt & Whitney hand	No. 2	.....	0.42
Pratt & Whitney hand	No. 2½	.....	0.42
Pratt & Whitney hand	No. 3	.....	0.80
Shapers:			
Lodge & Davis	14 in.	.....	0.35
Hendey	20 in.	.....	0.55
Hendey	24 in.	.....	0.52 to 0.7
Hendey	28 in.	.....	0.52 to 0.7
Tapping Machine:			
Pratt & Whitney	No. 2	.....	0.10

13. The horse-power values for individually driven machine too given in the following paragraphs are recommended by the Westinghou Electric and Manufacturing Co. As these values are based on avera practice, they may be decreased for very light work and must often be i creased for very heavy work. The recommended type of motor is indicat by the symbols A, B, C. (A) Adjustable-speed, shunt-wound, direct-curre motors are used wherever a number of speeds are essential. (B) Constan speed, shunt-wound direct-current motors are used where the speeds a attainable by a gear box or cone-pulley arrangement or where only o speed is required. (C) Squirrel-cage induction motors are used where dire current is not available. A gear box or cone-pulley arrangement must b used to obtain different speeds.

14. Boring machines

Motor A, B or C (Par. 13)		
Diameter of spindle (in.)	Maximum boring diameter (in.)	Horse power
4	20	7½
6	30	10
8	40	15

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15. Bolt and nut machinery

(a) Bolt cutters—motor A, B or C (Par. 13)		
Style	Size (in.)	Horse power
Single	1, 1¼, 1½	1 to 2
	1¾, 2	2 to 3
	2¼, 3½	3 to 5
	4, 6	5 to 7½
Double	1, 1½	2 to 3
	2, 2½	3 to 5
Triple	1, 1½, 2	3 to 7½
(b) Bolt pointers—motor B or C		
	1½, 2½	1 to 2
(c) Nut tappers—motor A, B or C		
Four-spindle	1, 2	3
Six-spindle	2	3
Ten-spindle	2	5
(d) Nut facer—motor B or C		
	1, 2	2 to 3

16. Bolt heading, upsetting and forging machines

Motor A,* B† or C‡ (Par. 13)	
Size (in.)	Horse power
¾ to 1½	5 to 7½
1½ to 2	10 to 15
2½ to 3	20 to 25
4 to 6	30 to 40

17. Boring and turning mills

Motor A, B or C (Par. 13)		
Size (in.)	Horse power	
	Average work	Heavy work
37 to 42	5 to 7½	7½ to 10
50	7½	7½ to 10
60 to 84	7½ to 10	10 to 15
Size (ft.)		
7 to 9	10 to 15	
10 to 12	10 to 15	30 to 40
14 to 16	15 to 20	
16 to 25	20 to 25	

* Speed variation is sometimes desired when different sizes of bolts are eaded on the same machine.
† Compound-wound, direct-current motor.
‡ Wound secondary or squirrel-cage motor with approximately 10 per ent. slip.

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18. Bulldozers

Motor B* or C† (Par. 13)		
Width (in.)	Head movement (in.)	Horse power
29	14	5
34	16	7½
39	16	10
45	18	15
63	20	20

19. Drilling machines

Motor A, B or C (Par. 13)	
(a) Sensitive machines up to ½ in. drill capacity	0.25 to 0.75 horse power
(b) Vertical drilling machines	
Size (in.)	Horse power
12 to 20	1
24 to 28	2
30 to 32	3
36 to 40	5
50 to 60	5 to 7½

(c) Radial drilling machines

Length of arm—ft.	Horse power	
	Average conditions	Heavy
3	1 to 2	3
4	2 to 3	5 to 7½
5, 6 and 7	3 to 5	5 to 7½
8, 9 and 10	5 to 7½	7½ to 10

20. Drilling, boring and milling machines

Motor A, B or C (Par. 13)	
Size of spindle (in.)	Horse power for single spindle
3½ to 4½	5 to 7½
4½ to 5½	7½ to 10
5½ to 6½	10 to 15

For machines with double spindles use motors of double the horse power given.

* Compound wound motor.

† Wound secondary or squirrel-cage motor with approximately 10 per cent slip.

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21. Drilling machines—multiple spindle

Motor A, B or C (Par. 13)		
Size of drills (in.)	No. of spindles	Horse power
⅛ to ¼	6 to 10	3
⅛ to ½	10	5
⅛ to ¾	10	7½
¼ to ¾	10	10
⅜ to 1	10	10 to 15
2	4	7½
2	6	10
2	8	15

22. Gear cutters

Motor A, B or C (Par. 13)	
Size (in.)	Horse power
36×9	2 to 3
48×10	3 to 5
30×12	5 to 7½
60×12	5 to 7½
72×14	7½ to 10
64×20	10 to 15

23. Grinders

(a) Tool, snagging, etc.—motor B or C (Par. 13)

Wheels		
No.	Diameter wheel (in.)	Horse power
2	6	½ to 1
2	10	2
2	12	3
2	18	5 to 7½
2	24	7½ to 10
2	26	7½ to 10

(b) Cylindrical—motor A, B or C (Par. 13)

Dia. wheel (in.)	Length work (in.)	Horse power	
		Average work	Heavy work
10	50	5	7½
10	72	5	7½
10	96	5	7½
10	120	5	7½
14	72	10	15
18	120	10	15
18	144	10	15
18	168	10	15

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23. Grinders.—*Continued*
Miscellaneous—motor B or C (Par. **13**)

	Horse power
Wet tool grinder	2 to 3
Flexible swinging, grinding and polishing machine	3
Angle-cock grinder	3
Piston-rod grinder	3
Twist-drill grinder	2
Automatic tool grinder	3 to 5

24. Hammers

Motor B* or C† (Par. **13**)

Size (lb.)	Horse power
15 to 75	½ to 5
100 to 200	5 to 7½

Drop-hammers require approximately 1 h.p. for every 100-lb. weight of hammer head.

25. Lathes—motor A, B or C (Par. **13**)
(a) Engine lathes

	Horse power	
Swing (in.)	Average	Heavy
12	½	2
14	¾ to 1	2 to 3
16	1 to 2	2 to 3
18	2 to 3	3 to 5
20 to 22	3	7½ to 10
24 to 27	5	7½ to 10
30	5 to 7½	7½ to 10
32 to 36	7½ to 10	10 to 15
38 to 42	10 to 15	15 to 20
48 to 54	15 to 20	20 to 25
60 to 84	20 to 25	25 to 30

(b) Axle lathes

		Horse power
Single		5, 7½, 10
Double		10, 15, 20

(c) Wheel lathes

Size (in.)	Horse power	
	Main-drive motor	Tail-stock motor‡
48	15 to 20	5
51 to 60	15 to 20	5
79 to 84	25 to 30	5
90	30 to 40	5 to 7½
100	40 to 50	5 to 7½

* Compound-wound motor.
† Wound secondary squirrel-cage motor with approximately 10 per cent. slip
‡ Standard machine-tool traverse motor.

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26. Milling machines

Motor A, B or C (Par. 13)

Vertical slab milling machines	
Width of work (in.)	Horse power
24	7½
32 to 36	10
42	15

Vertical milling machines

Height under work (In.)	Horse power
12	5
14	7½
18	10
20	15
24	20

Plain milling machines

Table feed (in.)	Cross feed (in.)	Vertical feed (in.)	Horse power
34	10	20	7½
42	12	20	10
50	12	21	15

Universal milling machines

Machine no.	Horse power
1	1 to 2
1½	1 to 2
2	3 to 5
3	5 to 7½
4	7½ to 10
5	10 to 15

Horizontal slab milling machines

Width between housings	Horse power	
(In.)	Average	Heavy
24	7½ to 10	10 to 15
30	7½ to 10	10 to 15
36	10 to 15	20 to 25
60	25	50 to 60
72	25	75

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27. Pipe threading and cutting off machines

Motor A, B or C (Par. 13)	
Size pipe (in.)	Horse power
¼ to 2	2
¼ to 3	3
1 to 4	3
1¼ to 6	3 to 5
2 to 8	3 to 5
3 to 10	5
4 to 12	5
8 to 18	7½
24	10

28. Planers

Motor B* or C (Par. 13)		
Width (in.)	Distance under rail (in.)	Horse power
22	22	3
24	24	3 to 5
27	27	3 to 5
30	30	5 to 7½
36	36	10 to 15
42	42	15 to 20
48	48	15 to 20
54	54	20 to 25
60	60	20 to 25
72	72	25 to 30
84	84	30
100	100	40

Normal length of bed in feet is about ¼ the width in inches.

29. Rotary planers

Motor A, B or C (Par. 13)	
Dia. of cutter (in.)	Horse power
24	5
30	7½
36 to 42	10
48 to 54	15
60	20
72	25
84	30
96 to 100	40

30. Polishing and buffing machines

Motor B or C (Par. 13)		
Wheels		Horse power
No.	Diameter (in.)	
2	6	¼ to ½
2	10	1 to 2
2	12	2 to 3
2	14	3 to 5

For brass tubing use double the above horse-power values.

* Compound-wound motor.

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31. Presses, hydrostatic wheel

Motor B or C (Par. 13)	
Size (tons)	Horse power
100	5
200	7½
300	7½
400	10
600	15

Presses for notching sheet iron or steel, motor A, B or C, ½ to 3 horse power.

32. Punching machines

Motor B* or C† (Par. 13)		
Dia. (in.)	Thickness (in.)	Horse power
¾	¼	1
¾	¼	2 to 3
¾	¼	2 to 3
¾	¼	3 to 5
¾	¼	5
1	¼	5
1	1	7½
1¼	1	7½ to 10
1¼	1	10 to 15
2	1	10 to 15
2½	1½	15 to 25

33. Rolls—bending and straightening

Motor B‡ or C§ (Par. 13)		
Width (ft.)	Thickness (in.)	Horse power
4	¼	5
6	⅜	5
6	½	7½
6	¾	15
8	¾	25
10	1¼	35
10	1½	50
24	1	50

34. Saws, cold and cut-off

Motor A, B or C (Par. 13)	
Size of saw (in.)	Horse power
20	3
26	5
32	7½
36	10 to 15
42	20
48	25

* Compound-wound motor.
† Wound secondary or squirrel-cage motor with approximately 10 per cent. slip on the larger sizes.
‡ Standard bending roll motor.
§ Wound secondary induction motor.

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35. Shapers, single head

Motor A, B or C (Par. 13)	
Stroke (in.)	Horse power
12 to 16	2
18	2 to 3
20 to 24	3 to 5
30	5 to 7½

Traverse head shaper

Stroke (in.)	Horse power
20	7½
24	10

36. Shears

Motor B* or C† (Par. 13)		
	Horse power	
Width (in.)	Cut ¼-in. iron	Cut ½-in. iron
30 to 42	3	5
50 to 60	4	7½
72 to 96	5	10
Bolt shears		7½ horse power
Double-angle shears		10 horse power

Lever shears

Motor B‡ or C§ (Par. 13)	
Capacity (in.)	Horse power
1 × 1	5
1½ × 1½	7½
2 × 2	10
6 × 1	
2½ × 2½	15
1 × 7	
2¾ × 2¾	20
1½ × 8	
3½ × 3½	30
4½ round	

* Compound-wound motor.
† Wound secondary or squirrel-cage induction motor with approximately 10 per cent. slip.
‡ Compound-wound motor.
§ Wound secondary or squirrel-cage motor with approximately 10 per cent. slip.

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Plate shears

Motor—B* or C†			
Size of metal cut (in.)	Cuts per min.	Length of stroke (in.)	Horse power
¾ × 24	35	3	10
1 × 24	20	3	15
2 × 14	15	4½	30
1 × 42	20	4	20
1½ × 42	15	4½	60
1½ × 54	18	6	75
1½ × 72	20	5½	70
1¼ × 100	10 to 12	7½	75

Tin-plate squaring shears

Motor—B or C		
Size of plates (in.)	Cuts per min.	Horse power
54 by 54 ⅛ packs	30	7½
72 by 72 ⅛ packs	30	7½

37. Slotters and key-seating machines

Motor A, B or C (Par. 13)			
Stroke (in.)	Horse power	Stroke (in.)	Horse power
6	3	16	7½
8	3 to 5	18	7½ to 10
10	5	20	10 to 15
12	5	24	10 to 15
14	5 to 7½	30	10 to 15

38. Comparison of five planer drives shown in Figs. 2 to 6 incl. is as follows:

Figure numbers	2	3	4	5	6
Drive, horse power	25.0	25.0	25.0	25.0	25.0
Stroke, feet	8.0	8.0	8.0	8.0	8.0
Approximate cutting load, horse power.	25.0	25.0	24.0	26.0	31.0
Peak load reverse to return, horse power.	55.5	45.3	75.0	25.0	20.0
Peak load reverse to cut, horse power	25.0	55.0	36.0	15.0	20.0
Time return stroke, seconds	7.2	7.2	7.6	6.8	5.6
Time cutting stroke, seconds	20.9	20.0	19.5	16.0	13.4
Time of cycle, seconds	27.2	27.2	27.1	22.8	19.0
Feet per minute, return stroke	66.6	66.6	63.2	70.5	85.7
Feet per minute, cutting stroke	24.0	24.0	24.6	30.0	35.8
Ratio cut to return, 1 to	2.78	2.78	2.57	2.35	2.4

* Compound-wound motor.

† Wound-secondary or squirrel-cage motor with approximately 10 per cent. slip.

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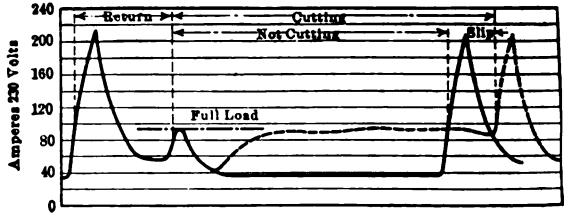


FIG. 2.—Single-belt drive.

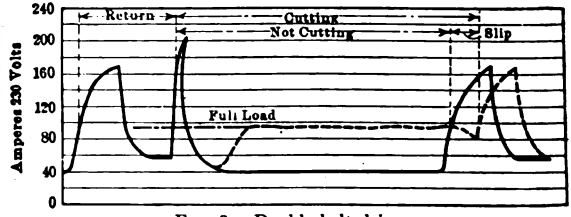


FIG. 3.—Double-belt drive.

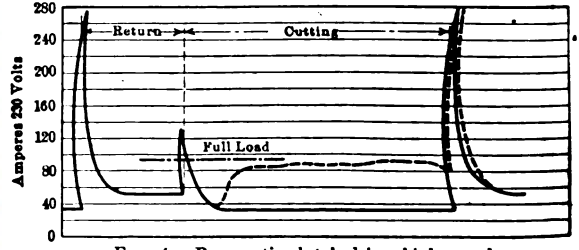


FIG. 4.—Pneumatic-clutch drive, high speed.

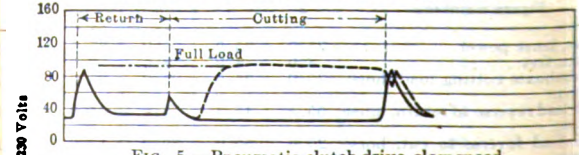


FIG. 5.—Pneumatic-clutch drive, slow speed.

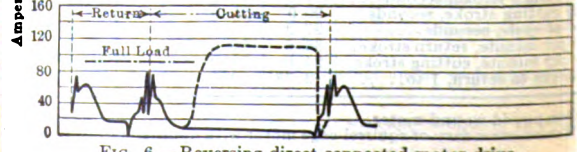


FIG. 6.—Reversing direct-connected motor drive.

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39. The direct-connected adjustable-speed reversing motor is the most recent development in motors for machine tools. It has been applied to planers, slotters, key-seaters, wire and tube drawing machines and large boring mills. Its advantages lie in increased production and saving of power. Figs. 2 to 6, inclusive show five planer drives.* These curves are drawn to the same scale and show the power required to drive "light" and with normal cuts, see Par. **38**.

40. Power required by portable armature drills
(Andrew Stewart, before Glasgow Techn. College Sc. Soc.)

Size of tool	Spindle rev. per min.	Wt. of tool, lb.	Diam. hole, in.	Depth hole, in.	Time sec.	Metal	Watts	Watts per lb. metal per min.†
Breast	800	13	$\frac{3}{4}$	1.5	65	Cast iron	305	7,200
1 M 1	450	17	$\frac{3}{4}$	1.0	120	Cast iron	330	4,230
1 M 2	250	30	$\frac{3}{4}$	0.5	40	Steel	495	8,448
1 M 2	250	30	$\frac{3}{4}$	1.5	70	Cast iron	660	3,300
1 M 3	150	32	1	1.5	120	Cast iron	550	3,666
1 M 3	150	32	1	0.5	80	Steel	495	6,447
1 M 3	150	32	$1\frac{1}{4}$	1.5	180	Cast iron	440	4,125
1 M 4	100	52	2	1.5	180	Cast iron	990	2,564
3 M 3	150	48	$1\frac{1}{4}$	1.5	120	Cast iron	770	3,200
3 M 4	100	58	$1\frac{1}{4}$	2.75	105	Cast iron	1,320	2,620
3 M 4	100	58	$1\frac{1}{4}$	3.0	240	Cast iron	1,540	3,286
3 M 4	100	58	2	2.0	150	Cast iron	1,880	2,940
3 M 4	100	58	$2\frac{11}{16}$	2.75	240	Cast iron	2,200	3,040
3 M 4	100	58	2	1.3	150	Mild steel	1,860	4,650

WOOD-WORKING MACHINERY

BY CHESTER W. DRAKE

General Engineer, Westinghouse Electric & Manufacturing Co., Member, American Institute of Electrical Engineers

SAWING

41. Band saws are replacing circular saws in most saw mills, since the saving they effect in the kerf much more than offsets their higher first cost, labor and maintenance charges. Band saws having wheels 8 ft., 9 ft. and 10 ft. diameter are in principal use and their power requirements vary widely with the kind and size of logs and the cutting speed.

42. Type of motor suitable for band saws. Induction motors, either of the squirrel-cage or wound-rotor type may be used for driving band mills, but special attention to the motor and control characteristics are necessary. The band wheels have a total weight of several tons, and when running at a saw speed of 10,000 ft. per min. have a very large fly-wheel effect. Consequently, a motor is required which has a high starting torque and is able to bring the mill to speed in about a minute. A squirrel-cage motor with a high slip (7 or 8 per cent.) will develop a high torque at starting, and besides this has the additional advantage due to its slip of allowing the band saw to slow down at times of heavy load, and give up some of its stored energy. In this way the load fluctuation on the motor and the system may be considerably reduced. A slip-ring motor gives a high starting torque, but with the secondary short-circuited has a low slip, and consequently the motor is subjected to all the instantaneous peaks of load. A permanent resistance may, however, be connected in the secondary circuit to give any desired slip. An advantage of this method is that the heat thus generated is external to

* Fair, Charles. *American Machinist*, Vol. XXXVIII, page 103.

† These figures include losses in the motor. Careful tests in which the motor losses were separated showed that the power utilised at the drill point varied from 3.13 to 4.1 kw. per lb. of mild steel per min. and from 1.57 to 2.69 kw. per lb. of cast iron per min., the low figures referring to 2-in. holes and the high ones to small holes.

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the motor. The squirrel-cage motor is simpler and somewhat more rugged, but has the disadvantages of having a fixed slip, of requiring a comparatively large current at starting and, with high slip, of radiating a large amount of heat. Both types are in satisfactory service but slip-ring motors are in more common use especially for the larger sizes of saws.

43. The average horse power required by band mills usually varies from 75 to 125 h.p. but to take care of heavy cuts and maintain the speed, motors of from 150 to 250 h.p. are usually supplied for each saw. These motors should preferably be of the 3-bearing belted type and with speeds from about 570 to 850 rev. per min. The following table shows the characteristics of motors which are now installed in saw mills and giving satisfactory service.

Motor		Band saw	
Horse power	Rev. per min.	Wheel diam. (ft.)	Width of saw (in.)
200	580	9	15
150	570	8	14
*150	675	9	14 double edge
200	850	9	.....
200	580	10	.....

44. Circular saws. When the head saw is of the circular type, both saws are usually driven by one belted motor, and, due to the larger kerf, more power is usually required than for band mills. The following drives are in actual operation.

Motor		Saws
Horse power	Rev. per min.	Diameter
250	580	2–60 in.
300	850	2–60 in. with carriage and live rolls

45. Resaws. Time can usually be saved by cutting planks and timber at the head saw and then resawing to the desired dimensions. Band resaws are in almost universal use, but circular resaws are sometimes installed. One 72-in. circular resaw in operation is belt-driven by a 100-h.p., 1,120-rev. per min. squirrel-cage motor. Band resaws are generally driven in the same manner as the head saws although for the smaller sizes the pulley speed is sufficiently high so that coupled motors become practicable. The following band resaws are in successful operation in saw mills.

Motor		Band resaw		
Horse power	Rev. per min.	Wheel diam. (in.)	Width of saw (in.)	Drive
125	850	72	10	Belted
75	850	†62	9	Belted
60	850	†54	6	Belted
35	580	60	5	Coupled

46. Edgers may in most cases be economically driven by coupled squirrel-cage induction motors. There is practically no fly-wheel effect in edgers, and motors are subjected to a severe and rapidly fluctuating load. Since one self-feed rip saw on 2-in. stock may easily require 25 h.p., it is seen that an edger with six or eight saws cutting 2-in. to 4-in. stock may at times require from 150 to 200 h.p. The actual load depends principally upon the kind of wood, feed and number of saws in the cut. The following motor-driven edgers are installed in saw mills.

* High-slip squirrel-cage motor.
† These are horizontal resaws.

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Motor		Saws	Drive	Remarks
Horse power	Rev. per min.			
200	850	6–32 in.	Belted	
150	850	8–32 in.	Coupled	
75	1,700	8–24 in.	Coupled	Larger motor required for stock over 2-in. thick.
50	1,700	4–18 in. 4–24 in.	Coupled	See test below
50	850	6–24 in.	Belted	Saws run 1,590 rev. per min.
30	3,480	2–6 in.	Coupled	Lath edger

Test on the above 50-h.p. coupled motor showed a friction load of 6 kw. With a feed of from 180 to 190 ft. per min., on hemlock stock, the following results were obtained:

4 cuts in 3-in. stock..... 68 kw., peaks reaching 75 and 80 kw.
2 cuts in 6-in. stock..... 68 kw., peaks reaching 75 and 80 kw.

47. Trimmers. The driving shafts of trimmers can be readily driven by coupled squirrel-cage motors and speeds of 680 to 850 rev. per min. are customary. The following are instances of successful applications.

Motor		Saws	Drive	Remarks
Horse power	Rev. per min.			
50	680	20–30 in.	Coupled	
50	850	21–32 in.	Coupled	Also drives transfer chains.
30	850	12–24 in.	Coupled	
5	1,120	2–18 in.	Coupled	Lath bundle trimmer

48. Slashers are best driven by standard squirrel-cage motors coupled to the saw shafts. The speed is determined by the saw diameter since it is not desirable to use a cutting speed much higher than 10,000 ft. per min. The following are typical installations.

Motor		Saws	Drive
Horse power	Rev. per min.		
50	850	14–40 in.	Coupled
40	580	6–36 in.	Belted
30	850	5–46 in.	Coupled
25	1,120	6–38 in.	Coupled
20	850	4–36 in.	Belted

49. Hogs. The rotating element of a hog is very heavy and the discussion of squirrel-cage versus slip-ring motors (Par. 42) applies here also.

Diamond Iron Works' hogs

No.	Style	Rotor		Capacity	Horse power
		Diam. (in.)	Rev. per min.	Cords per hr.	
1	B	60	650	16	65
1½	B	48	825	12	50
2	B	34	1,000	10	40
3	S	48	825	16	75

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Test on a No. 1 hog driven by a 75-h.p., 690-rev. per min., slip-ring coupled motor gave a friction load of 25 kw. Average load with feed from two band mills, 40 to 50 kw. Peaks 90 kw.

Unless the hog is carefully fed the motors are subject to severe load fluctuations.

50. Miscellaneous

Drop cut-off saw, 72 in. diam., 510 rev. per min.; 20-h.p. 570-rev. per min. motor, belted.
Lath bolter, 5 12-in. saws; 40-h.p., 1,700-rev. per min. motor, coupled.
Log haul, 230 ft. total length, 100 ft. on 60 per cent. grade; 30-h.p., 1,130-rev. per min. motor, belted.
Conveyors in mill; 5 to 15 h.p. according to conditions, usually back-geared or belted through a counter-shaft.
Covel band saw grinder; 3-h.p., 1,120-rev. per min. motor, back-geared.

PLANING MILLS

51. Selection of motor. Standard squirrel-cage induction motors are satisfactorily applied to almost all machines used in planing and other wood-working establishments with, perhaps, the exceptions of large band resaws of great inertia, heavy planers and matchers with considerable static friction which must be overcome at starting, and in cases where each individual motor requires a large percentage of the generator capacity. For these special cases slip-ring motors are used. The data in the following paragraphs give the average sizes and the power requirements of machines as supplied by several of the leading manufacturers. Nearly all of these machines have met practical service with the motors as indicated, although for very light or for very heavy service, smaller or larger motors, respectively, are sometimes used.

52. High-speed induction motors. Various machine designs have been made for planers, jointers, shapers, etc., using 2-pole (3,600 r.p.m.) 60-cycle squirrel-cage motors with a view of eliminating belts and making the motors integral with the machines. This speed has been found too low for most cutting heads, but the advantages of self-contained units warranted in many cases the installation of induction frequency changers which with two- or four-pole induction motors would give the desired speed. Most applications are satisfactorily taken care of with frequencies from 100–180 cycles giving motor speeds from 6,000–10,800 r.p.m., but frequencies as high as 300 cycles are sometimes used for small grinders or carving machines. Special attention should be given to mechanical details, such as bearings, lubrication, alignment and balance when using high-speed motors. For a description of the construction and operation of induction-frequency changers, refer to Sec. 7, Par. **354.**

53. Band saws

Scroll and rip			
Wheel diam. (in.)	Max. width of saw (in.)	Feed (ft. per min.)	Aver. horse power
30	½	Hand	2
34–38	½	Hand	3
40	3	60–150	10
42	½	Hand	5
42	3½	60–200	15
48	1½	Hand	7½

Resaw and combination scroll and resaws			
38	2	20–42	7½
40	3	20–42	10
44	4	18–60	15
48	5	20–120	20
54	6	24–140	30
60	8	24–145	40

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44-in. band rip and resaw. Berlin No. 282 44-in. ×4-in. wheel, 680 rev. per min., geared to a 15 h.p. 1,120 rev. per min. squirrel-cage motor. Friction load 4 kw. Resawing 6-in. to 8-in. poplar, 24 ft. per min.; average load, 12 kw.

54-in. band resaw. Mershon saw, 540 rev. per min., belted to a 20-h.p 1,120 rev. per min. squirrel-cage motor; friction, 5.5 kw. Resawing oak 4 in. to 6 in. wide, 70 ft. per min.; average load, 18 kw.; peaks, 21 kw.

Horisontal band resaw. Berlin No. 287 hopper feed, width of hopper 26 in.; belted to a 40 h.p., 850-rev. per min. squirrel-cage motor; friction load, 9 kw.; tests, sawing oak.

Width (in.)	Feed (ft. per min.)	Load (kw.)	
		Average	Peaks
13½	30	32	50
24	22	44	50

54. Circular saws

Cut-off saws		Combination benches, dado, etc.	
Diam. (in.)	Aver. h.p.	Diam. (in.)	Aver. h.p.
10–14	3	12–16	5
16	5	20	7½
*16	7½	.....	.....
24	7½	.....	.....
30	10	.....	.....
†32	25	.....	.....
36	15	.....	.....

Rip saws

Diam. (in.)	No. of saws	Feed (ft. per min.)	Aver. h.p.
12–14	1	Hand	5
16–20	1	Hand	7½
14–16	1	65–200	10–15
16	2	50–160	20
36	1	Hand	20
36	1	50–160	30

Self-feed rip saw. 13-in. saw, 2,250-rev. per min., belted to a 10 h.p., 1,700-rev. per min. squirrel-cage motor; friction load, 2.5 kw.

Stock	Feed (ft. per min.)	Aver. load (kw.)
1 in. oak	73	5
1 in. oak	116	7.5
1 in. oak	150	9.2
2 in. hemlock	150	12.5

Resaws

Diam. (in.)	Feed (ft. per min.)	Aver. h.p.
24–30	30–80	15
36–42	30–80	20
48	30–80	30

* Double cut-off or trimmer.
† Double automatic cut-off.

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55. Jointers

Width (in.)	Aver. h.p.
8–12	2
16–24	3
30–36	5
Glue jointers	3–5

56. Surfacers

Capacity (in.) width and height	No. of feed rolls	No. of heads	Feed (ft. per min.)	Aver. h.p.
18×6	2	1	22–32	5
24×7	4	1	18–32	7.5
24×8	4	2	20 35	10
24×6	6	2	30–45	15
24×8	6	2	40–80	30
24×8	4	2	40–80	20
30×6	4	2	30–50	20
30×8	6	2	40–100	30
30×7	4	2	16–50	15

57. Planers, matchers and flooring machines

Capacity (in.)	No. of rolls	No. of heads	Feed (ft. per min.)	Aver. h.p.
9×6	6	4	40–80	30
15×6	6	4	40–102	40
15×8	4	4	30–45	30
24×6	6	4	59–104	40
24×8	6	5	40–80	40
30×8	6	4	40–80	40

Planers and matchers. Berlin No. 94 15-in. P. & M. with a 30-h.p., 1,120-rev. per min. squirrel-cage motor coupled to countershaft; friction load, 2 heads, 8 kw. Double-surfacing 12-in. wet oak at 60 ft. per min., reducing from 1½-in. to ⅞-in., required average of 30 kw., peaks 40 kw.

Hoyt No. 33 19-in.×8-in. P. & M. belted to a 30-h.p., 1,120-rev. per min. squirrel-cage motor; friction load, 2 heads, 8 kw.; 4 heads, 12 kw. Double-surfacing cypress 12 in. wide, reducing from 1-in. or 1½-in. thick to ¾ in. thick, feed 50 ft. per min.; average load, 18 kw.; oak, same cut as above, 22 kw., peaks 32 kw.

58. Timber sizers

Cap. (in.)	No. of rolls	No. of heads	Feed (ft. per min.)	Aver. h.p.
20×12	8	4	25–85	50
20×16	6	4	25–85	40
30×20	8	4	25–85	50

For extra-heavy service, 75 h.p. is sometimes required.

59. Tenoning machines

	Aver. h.p.
Single end, hand feed, average duty	5
Double end, hand feed, average duty	10
Double end, power feed, average duty	15
Automatic blind slat tenoner	3

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60. Outside moulders or stickers

Cap. (in.)	No. of heads	Feed (ft. per min.)	Aver. h.p.
4×4	1 and 2	12–68	5
Sash	2 and 3	20–35	5 to 7.5
4×4	3 and 4	12–68	7.5
6×4	4	15–66	10
10×4	4	10–60	15
10×8	4	14–80	20
12×5	4	10–60	20
14×5	4	10–60	20

61. Mortising machines

Size of chisel or bit (in.)	Description	Aver. h.p.
¼ to 1	Hollow chisel sash	3
¼ to 1	Chisel mortiser with borer	3
¼ to 1½	Horizontal automatic hollow chisel	5
Up to 2½	Vertical automatic hollow chisel	7.5
	Chain mortisers	3

62. Sanding machines

Drum sanders

Face of drum. (in.)	No. of drums	Aver. h.p.
30	3	7.5
36 42	3	10
48–54	3	15
60–66	3	20
72	3	25
84	3	30
30–36	2	7.5
42–48	2	10
30–36	1	5
42	1	7.5

Sanders. Berlin 42-in. 3-roll Invincible belted to a 15-h.p., 1,120-rev. per min. squirrel-cage motor; friction, 3.2 kw.; sanding oak 6 in. wide, average load, 4 kw.; sanding oak 27 in. wide, average load, 8 kw., peaks, 9 kw.

Belt sanders

No. and width of belts	Aver. h.p.
2– 6 in.	3
1– 6 in.	2
1–14 in.	3
1–18 in.	5

Combination sanders

Drum and spindle	13 in.×16 in. drum 1¼ to 4 in.×7½ in. spindle	Aver. 3 h.p.

Column, post or arm sanders

8 in. diam. disc	Average 3 h.p.

Disc sanders

Two discs, 36 in. to 48 in. diam	Average 3 h.p.

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63. Shapers

Single spindle—3 h.p.	Double spindle—5 h.p.

64. Linderman automatic dovetail glue jointer. This machine may be driven by one motor and countershaft, or by three motors. Size is given by the maximum length of lumber which can be jointed.

Size, ft.	Horse power			
	Group drive	Individual drive		
		Left	Right	Saw
3–4–5	15	5	7.5	5
6–7–8–10	20	7.5	10	5
12–14–16	25	7.5	15	5

65. Nailing machines. (Mayes Mach. Co., N. Y.)
Size No. 1 drives 6 nails 1 in. to 1¼ in. long, any gage; will nail a box which is 2 in. to 18 in. deep, of any length average, 2 h.p. No. 6 Combination nailing machine and clincher, feeds 16 nails 1½ to 2¾ in. long, and clinches 1½-in. nails; will nail a box 40 in. square: average, 5 h.p.

66. Lathes.

Speed lathes	0.5 to 1 h.p.
Pattern lathes 16 to 20 in. swing	3 h.p.
Pattern lathes 24 to 32 in. swing	5 h.p.
Automatic back-knife lathes	5 to 15 h.p.

67. Carving machines: 1 to 2 h.p.

68. Knife grinders.
Automatic self-feed wheel 26 in. × 1½ in., 30 in. to 50 in. long, 3 h.p.
Automatic cup-wheel grinder, wheel 8 in. × 4½ in. 29 in. to 32 in. long, 3 h.p.

69. Panel raiser: hand feed, 3 h.p.; power feed 5 h.p.

70. Excelsior machines. Lewis T. Kline 8-block horizontal machine, capacity 2 tons of wood wool or 5 to 6 tons of coarse excelsior per 10 hr.; average load, 30 to 40 h.p.

TRAVELING CRANES

BY ARTHUR C. EASTWOOD

President, Electric Controller and Manufacturing Co., Fellow, American Institute of Electrical Engineers

71. Standard electric overhead traveling cranes. These cranes are in general characterized by the fact that they travel upon an overhead structure. Usually they are supplied with three motors, one for operating the hoist, one for propelling the bridge along the runway, and one for propelling the trolley carrying the hoisting mechanism backward and forward across the bridge girders of the crane. In special cases the trolley may be equipped with two or more separate hoisting mechanisms, and in some instances two entirely separate trolleys, each equipped with its own hoisting and trolley motor, are used.

72. Gantry cranes. These cranes, as far as functions are concerned, are similar to electric overhead traveling cranes, but are characterized by the fact that in place of traveling on an overhead runway, the bridge member of the crane is supported on structural legs of suitable height, which are provided with wheels and suitable gearing, so that the crane may be propelled bodily along tracks on the ground.

73. Telpherage systems are treated fully in another portion of this section, Par. **227** to **239**.

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74. Jib cranes comprise suitable jibs or booms, provided with motor-driven hoisting tackle. In some cases, also, a motor with suitable gearing is provided for swinging the jib into different positions.

75. Electric locomotive cranes comprise a jib or boom, usually carried by a turn-table which is mounted upon trucks. Frequently individual motors are provided for raising and lowering the boom, for rotating the boom, for hoisting the load, and for propelling the machine along the tracks. In other cases only a single motor is used, the different functions being set into operation through mechanical clutches.

76. Miscellaneous. Under this head may be mentioned charging cranes for open-hearth steel furnaces, skip hoists for elevating and dumping ore, coke, etc., into blast furnaces, also special cranes and unloaders for unloading bulk cargoes, such as ore or coal, from vessels.

77. Types of motors. The type of motor most commonly used for operating the various motions of cranes is the series-wound, direct-current motor. The series-wound motor is admirably adapted to the purpose because under heavy load it has the tendency to slow down, thus relieving the power station of a heavy load fluctuation; on the other hand, in the case of light loads, the motor speed increases, thus producing what is generally known as a "lively" crane. Compound-wound direct-current motors are used only in special cases. Where alternating current is available, and its conversion into direct current would entail a very considerable expense, alternating-current motors may be used. The preferable type of alternating-current motor for this service is the slip-ring type, in which resistance is introduced in the rotor circuit in order to obtain variation in speed. This type of motor affords much better results, as far as torque and speed variations are concerned, than the squirrel-cage motor, the torque of which decreases very rapidly as the voltage applied to the terminals of the primary winding is reduced. The speed range of both of these types of alternating-current motors is limited and hence they do not produce nearly so active a crane as one equipped with direct-current series-wound motors. In many large industrial plants, covering considerable areas, energy is generated and distributed in the form of alternating current. The motors which require but slight speed variation are operated directly from the alternating-current mains, while synchronous converters or motor-generator sets are installed to produce direct current for the operation of cranes, hoists, and other machines which must operate through a wide range of speed and under greatly varying load.

78. The selection of the proper normal rating of hoist motors* to be used is in general a difficult problem on account of wide variations in service requirements, particularly as to the matter of frequency of operation. As an illustration, two extreme cases may be taken: 1st, that of a crane installed in an engine room or pump house, the crane having been installed originally to assist in erecting the heavy machinery, being subsequently used only at varying and infrequent intervals for lifting parts of machinery when it becomes necessary to make adjustments or repairs; 2nd, the case of a traveling crane provided with a lifting magnet for handling pig-iron or other magnetic material in bulk, or equipped with a grab bucket for handling coal, sand, slag, etc. There are instances of the operation of cranes of this type four times per min., practically 24 hr. per day for indefinite periods, the lifted load being practically constant in value and almost equal to the rated capacity of the crane. It is obvious that in the first case cited, the heating of the motor windings presents a small problem, while in the latter case this item is of paramount importance. Of course the torque exerted by the hoist motor in lifting the maximum load which will be encountered, must be taken into consideration in both cases. If possible the cycle of operations should be considered as follows: 1st, the time required to hoist with maximum load; 2nd, the period of rest at the upper limit of travel; 3rd, the time of lowering; 4th, the period of rest at the lower limit of travel before the next cycle is started. The current required in lowering with a mechanical brake, or the current required in dynamic braking (Par. **83** and **537**) must also be taken into consideration. These figures known, they may be plotted in terms of time and current, so that the square-root of the mean-square current may be

* See "Horse Power of Crane Motors," *Machinery*, Dec., 1913, page 286.

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determined. Since practically all series-wound motors are given fairly definite ratings in terms of current which the motor can carry continuously for 1 hr. without overheating, the proper motor may thus be selected. In many cases, however, such as in the design of cranes for ordinary machine-shop service, where the full capacity of a hoist is brought into play infrequently, the judgment of the crane designer must be relied upon to determine the proper size of the hoist motor. Many crane builders find it convenient from the viewpoint of standardization of manufacture, to build trolleys of a given hoisting capacity in duplicate. In some applications of these standard cranes the hoisting motor may have much greater capacity than is required, while in other cases the work which must be performed by the hoist may prove to be greater than was anticipated, necessitating adjustments in the field.

79. **The magnetic brake.** The hoisting motor of a crane is usually provided with a magnetic brake. This brake is so arranged that only when power is applied to the hoisting motor is the brake released. At all other times the brake is set either by means of a weight or a sufficiently powerful spring. These brakes are ordinarily designed to apply on the armature shaft of the motor at the commutator end. The series-wound brake (in connection with direct-current motors) is by all means the safest and the most reliable. Shunt-wound brakes of course are necessary in connection with alternating-current hoisting motors, because a series-wound brake would act as a choke coil and materially reduce the voltage at the motor terminals.

80. **Types of brakes in common use,** see Par. **532** to **536.**

81. **Brake lining.** In present practice the friction members in all the types of brakes mentioned above are lined or faced with a composition of asbestos, woven together with bronze wire. This material affords a very much higher and much more constant coefficient of friction than do the leather, wood or metal brake facings used in the past.

82. **The mechanical brake.** After a load has been hoisted, it is usually necessary that it be lowered, at least a certain distance. If no means were provided for checking the lowering speed, the load might soon attain almost the speed of a freely falling body, and in the case of a series-wound hoisting motor, might soon attain a speed which would destroy the motor. On electric overhead traveling cranes a so-called "mechanical brake" has been employed, this brake being so designed as to prevent the load from appreciably accelerating the hoist motor, when it is running in the lowering direction, or from "overhauling" the motor, as this action is commonly designated. Many ingenious designs of such brakes have been developed. All of them, however, act upon the common principle that if the load begins to overhaul the motor, the brake is applied.

83. **Dynamic braking.** During recent years this method of retarding the speed of the hoisting motor when lowering a load has been quite generally adopted on electric cranes. The hoisting motor is driven as a generator by the lowering load, and is caused to generate energy which is either returned to the line or dissipated through a resistance, or both. This generation of energy imposes a magnetic drag on the machine and thus retards the downward speed of the load. Dynamic braking with a series-wound hoist motor is accomplished by connecting the field winding in series with a resistance across the supply mains, thus giving the machine the characteristics of a separately-excited shunt-wound generator. In some cases the armature is connected in a local circuit containing a resistance which may be varied at the will of the operator. In other cases the armature is connected across the supply mains in series with a resistance which may be varied by the operator, this latter connection being the one most generally used. See Par. **539.**

84. **Motor control in dynamic braking.** Fig. 7 is a diagram of wiring connections of a face-plate type of controller arranged for dynamic braking. When the load is traveling in the lowering direction, the resistances in series with both the armature and the field of the motor may be varied by the operator by manipulation of the lever of this controller. In hoisting, the motor is connected as an ordinary series-wound motor, the controlling resistance being in series with the motor circuit and varied to vary the hoisting speed. In lowering, however, it will be seen that the

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armature and the field are connected in separate circuits. On the first point of the controller, in lowering, the field is excited through a resistance which allows practically full-load current to pass through the field winding; also a considerable amount of resistance is included in the armature circuit. It will be seen that on the first lowering point the armature is shunted by the field winding and the brake winding. This naturally produces an extremely low speed. As the controller lever is moved from step to step, the resistance in the field circuit is increased, while the resistance in the armature circuit is decreased. Increase in resistance in the field circuit naturally reduces the field excitation and counter e.m.f., thus allowing the speed to increase. The resistance in the field circuit is ordinarily so proportioned that the speed can increase as much as 100 per cent. to 150 per

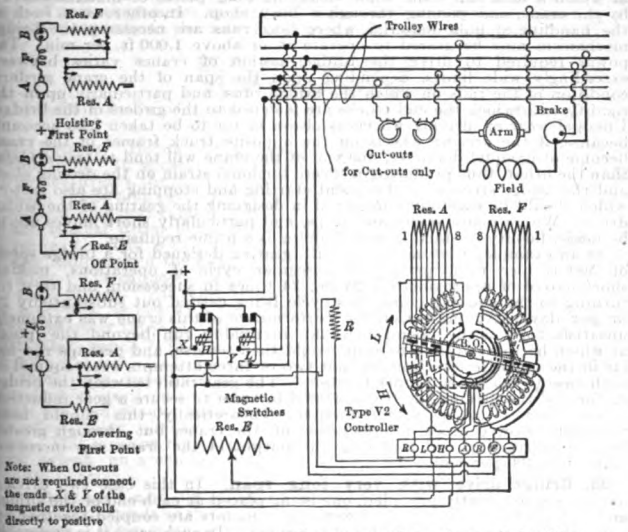


FIG. 7.—Face-plate type controller arranged for dynamic braking.

cent. above normal full-load speed. It will be seen that at all times the field is supplied with current from the mains, and at full speed this may amount to only half of the full-load current. On the other hand, the armature is also connected to the supply mains, and as soon as the counter e.m.f. reaches a value sufficient to overcome line voltage, current is actually returned to the line, so that the net current required in lowering the load is the difference between the current supplied to the field from the line and the current returned to the line by the armature. In lowering heavy loads the current returned to the line is greater than the current drawn from the line by the field, so that the lowering load is made to do useful work.

85. Slow-hoisting motor control. This type of control differs from the one illustrated in Fig. 7 only in the respect that a shunt is placed around the armature in order to reduce the speed, thus producing an extremely slow hoisting speed. This type of controller is frequently used in foundries where extremely slow speeds are required in lifting patterns from flasks, etc.

86. Limit stops are now customarily provided in connection with the hoisting motion of cranes and hoists. In the absence of a limit stop, the hoisting block, perhaps carrying a load, might be carried upward into

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the mechanism of the trolley, provided the operator did not open his controller at the proper time. Where the block of the hoist must be frequently run up to a point very close to the mechanism of the trolley, it is advisable to use a limit stop which not only cuts off the current from the motor, but includes the motor in a dynamic braking circuit of such low resistance that the hoist is stopped almost instantly, irrespective of the condition of the brake.

87. Drive of the crane bridge. The designed speed of crane bridges varies between very wide limits. In the case of cranes used in machine shops, structural shops, and plants of like nature, it is advisable to have the bridge of the crane driven at a speed of from 250 to 300 ft. per min. This corresponds to between 3 and 3½ miles per hr. which is a speed at which a man can walk while steadying long pieces of material carried by the crane, and passing through a busy shop. In other cases, such as the handling of bulk material, where long runs are necessary, the bridge mechanism may be geared to operate at or above 1,000 ft. per min. The power required to drive the bridge motion of cranes varies between exceedingly wide limits, depending upon the span of the crane girders, condition of the rails on which the bridge runs, and particularly upon the rigidity with which the end trucks are fastened to the girders of the bridge. Unequal wear of driving wheels is also a factor to be taken into account because, if the driving wheels on the opposite truck frames of the crane become of unequal diameter, one end of the crane will tend to travel faster than the other, thus producing a severe torsional strain on the driving shaft and the bridge structure. Frequent starting and stopping are also factors which should be carefully considered in designing the gearing of the bridge drive. Where many starts and stops, and particularly short moves are to be made, facility in starting and stopping is a prime requisite.

As an example, a certain crane with gearing designed for a bridge speed of 500 ft. per min. performed a regular cycle of operations, making short moves of approximately 24 in., 24 times in succession, and then returning to the starting-point, this cycle being carried out substantially 24 hr. per day. At the outset the performance of this crane was extremely unsatisfactory, as the operator would invariably run beyond the point at which he was required to stop, would then reverse, and perhaps run too far in the opposite direction, so that two or three attempts were required in each case to reach the proper position. The gear ratio between the bridge motor and the driving shaft was altered in order to secure a gear reduction of three times the original reduction. Theoretically, this should have materially slowed down the operation of the crane, but through greater facility in starting and stopping, the output of the crane was increased more than 400 per cent.

88. Bridge drive with very long span. In this case two driving motors are frequently provided, one being placed at each end of the bridge and driving the truck wheels directly; the motors are coupled together by a line shaft carried on the girder of the crane. In such cases it is preferable to connect the two driving motors in parallel and to provide each of them with a separate reversing switch, so that each will have its own connections to the line.

89. Safety devices. Under this heading might be mentioned limit stops, as described in Par. **86**, and also what are known as crane switchboards. These boards usually include two solenoid-operated switches or contactors which connect all of the circuits of the crane to the main feed wires. When these switches are open, all wiring on the crane is disconnected from the line. These switches are controlled by a plug, which, when pushed in, energizes the windings of the switch solenoids and causes the switches to close; when pulled out, it opens the switches, thereby interrupting the energy supply. The plug is also provided with attachments whereby it may be positively locked in the open position by a padlock. When a motor inspector or repairman mounts the crane he pulls open the plug and locks it positively in the open position, so that the crane cannot be operated until he has finished his work and removed his padlock. In addition the two magnetic switches are usually arranged for overload protection, and are operated by the action of overload relays in the circuit leads of each motor on the crane. In case the overload is merely temporary, the operator is simply required to reset the magnetic switches, which are conveniently at hand

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If, however, the overload relays continue to act when energy is applied, the operator must necessarily look for trouble in the mechanism of the crane.

90. Energy supply. In a plant in which a large number of cranes are employed, it is by no means necessary to provide generator capacity equal to the total rated horse power of all of the motors used. In a large industrial plant in which 127 cranes were installed, generator capacity corresponding to 25 per cent. of the total rated horse power of motors used on the cranes was found ample to care for the load. Where only a single crane is installed it is wise to provide generator capacity sufficient to take care of full-load on the hoist and bridge motions, leaving it to the overload capacity of the generator to take care of the current required by the trolley, in case all three motions of the crane should be operated at the same time. Naturally, the larger the number of cranes installed in a given plant where a definite cycle of operations is not carried out, the smaller may be the proportion of generator capacity to the total horse power of the crane motors.

ELECTRIC HOISTS

BY WILFRED SYKES

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91. Drums. Hoists are generally classified according to the shape of the drum. In general use are the cylindrical, the conical and the cylindro-conical drums, the last mentioned being a combination of the first two, part of the drum being cylindrical and part conical (Fig. 9). The object of the conical drum is to reduce the starting torque, as the load is exerted on the drum at a smaller radius when the cage is at the bottom of the shaft. The cylindro-conical drum is used with the same object. All other things being equal, the rope wear is less with the cylindrical drums than with other types of drums.

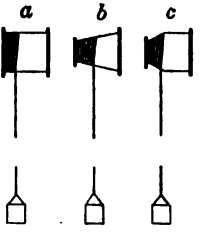


FIG. 8.—Unbalanced hoists.

92. Flat ropes. The above types (Par. 91) use round ropes, Flat ropes, generally about 0.5 in. thick, are sometimes used, the rope being wound upon itself on a reel, so that the radius at which the load is suspended gradually increases, the effect being similar to that of the conical drum. Flat ropes on reels are used only to a very small extent, on account of the excessive maintenance charges.

93. Balanced and unbalanced hoists. When running balanced the empty cage descends as the loaded cage ascends, the cages and cars balancing each other. When working unbalanced only one cage is used, and the load,

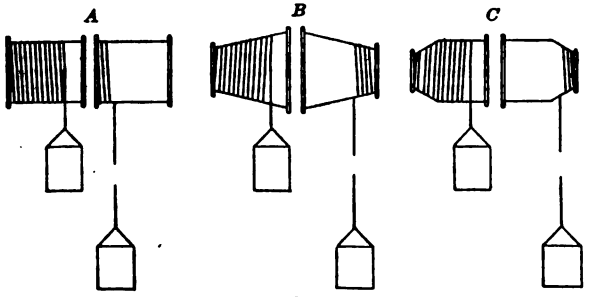


FIG. 9.—Balanced hoists.

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due to the cage and the car, must be added to that due to the weight of the material hoisted in order to ascertain the load on the motor. See Figs. 8 and 9.

94. Power requirements. In the case of small or medium-sized hoists it is usually difficult to determine a definite hoisting cycle, although the maximum load to be hoisted can generally be assumed. In such cases the rating of the motor required is usually determined from the following formula:

$$\text{h.p.} = \frac{L \times V}{33{,}000 \times 0.8} \qquad (1)$$

Where L = total unbalanced load and V = speed of hoisting in ft. per min.

For large hoists, the cycle of operation is usually well defined, and the required motor rating can be accurately determined. The calculation of load diagrams will be found useful in such investigation.*

95. Mechanical efficiency. The over-all efficiency of the mechanical parts of the equipment is assumed in general to be 80 per cent.

96. Service affecting motor rating. As the service is intermittent and as the motors have an opportunity to cool during the intervals between trips, it is not necessary that the motor should be capable of continuously carrying the load as determined above (Par. **94**). In order to preserve a good balance between the maximum torque capacity of the motor and its heating capacity, at the same time keeping down the cost, intermittent-rated motors are used for such hoists. Experience has shown that if a motor has sufficient capacity to carry the load, as determined above, for half an hour continuously, it will operate the hoist under ordinary conditions. In cases of very severe service, where the hoist operates a large portion of the time, and where the peak loads due to acceleration may be high, such a simple rule cannot be used.

97. Types of motors adaptable to hoists. Direct-current motors for small hoists are usually series-wound, but occasionally compound-wound motors are adopted, in order to simplify the control if dynamic braking is required. With an alternating-current supply, slip-ring motors are used, being designed for great momentary overload capacity. The high value of maximum torque for which these motors are designed necessitates a large magnetizing current, and usually such motors cannot be run continuously even at light load. For small and moderate-size hoists, motors having speeds from 300 to 500 rev. per min. are generally used, being connected to the drum through single-reduction gearing. Large induction motors, designed for direct-connection to hoists, have been built in a few cases where the speed has been in the neighborhood of 100 rev. per min. Such machines are very expensive and rather unsatisfactory from an operating standpoint. The difficulty of controlling large machines by rheostat practically confines the large motors to direct-current machines used in conjunction with a fly-wheel motor-generator set, or a plain motor-generator set (Par. **100** and **104**).

In the case of hoists operating under severe conditions when the average rotating speed of the motor over the whole cycle is low, and especially in the case of direct-current hoist motors working with constant field excitation which is not interrupted during periods of rest, it has been found desirable to use forced ventilation. For this purpose, the back end of the motor is enclosed and air forced through the machine by a constantly running fan. In this way the cooling of the motor goes on continuously whether it is rotating or not. Unless this is done the rate of cooling when the motor is at rest is very slow and excessively large machines would be required to keep the heating within permissible limits. Usually this is only necessary if the hoist must run at full capacity for long periods and in the case of machines of 500 h.p. and over.

98. Direct-connected and geared motors. Direct-current machines can be built in all sizes for comparatively slow speeds, 60 to 75 rev. per min. being quite common for machines of 500 h.p. and upward. The use of machine-cut double-helical gears has made possible the gearing of large hoist motors in many cases, and the very satisfactory operation of this type

* Sykes, Wilfred. "Large Electrically-driven Hoists," *Transactions* American Institute of Electrical Engineers, 1910.

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gearing when properly built is a strong argument in favor of using moderate-speed motors instead of the extremely slow-speed motors necessary for direct-connection.

99. Balancing systems. The high peak loads, caused by hoists of large capacity, especially during their periods of acceleration, make it desirable in many cases to adopt some system of making the load on the line more uniform. Practically all balancing systems utilise a fly-wheel, the speed of which is varied, so that it gives up or absorbs energy according to the demands of the hoist. The main requirements of a balancing system are that it should be capable of preventing sudden excessive demands for energy from the line, it should be automatic in operation, and that the losses, due to it, should be as low as possible.

100. Ilgner balancing system. The arrangement now most widely used, was devised by Mr. Karl Ilgner. As arranged for alternating-current supply, it consists of an induction motor with a wound rotor, coupled mechanically to a direct-current generator, which in turn supplies energy to a direct-current separately excited hoist motor. The motor-generator set is supplied with a fly-wheel of sufficient capacity to care for the peak loads. The field

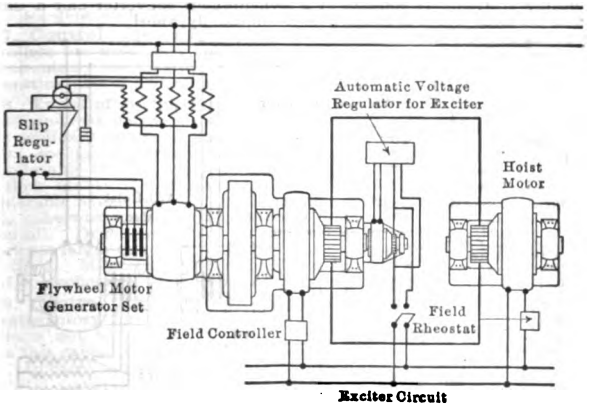


FIG. 10.—Ilgner balancing system.

of the direct-current generator is separately excited, and a controller is provided so that the excitation and the polarity of the generator can be varied as desired. The field polarity of the hoist motor remains constant, so that by reversing the armature current the direction of rotation can be changed. By varying the excitation of the generator, the voltage applied to the armature of the hoist motor can be varied, and in turn the speed of the hoist.

101. Action of the automatic regulator. A regulator is provided for automatically inserting resistance in the rotor circuit of the induction motor, thereby reducing the speed of the motor-generator set, which causes the fly-wheel to give up part of the energy stored in it. The rate at which the speed is changed depends upon the difference between the input that is to be maintained on the induction motor and the power required to drive the generator. When the load on the generator is reduced below the value for which the automatic regulator is set, the fly-wheel speed is increased by automatically removing resistance from the rotor circuit, energy being stored in the fly-wheel in order to enable it to carry the peak load, due to the succeeding cycle.

102. Details of Ilgner balancing system. This system provides not only for power equalisation, but also for the control of the hoist motor

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by the manipulation of the generator excitation, thereby eliminating rheostatic losses, and the difficulty of controlling large machines. The general arrangement of this scheme is shown by Fig. 10. In practice the speed of the fly-wheel set is varied from 15 to 20 per cent. during a hoisting cycle. High-speed fly-wheels with peripheral speeds reaching 25,000 ft. per min. are used in order to minimize the weight.

103. The losses with the Ilgner system are comparatively high, and it is seldom that an over-all efficiency of more than 50 per cent. is realized from the combined electrical and mechanical equipment. This efficiency decreases when the hoist is operated below its normal capacity, due to the constant no-load loss of the fly-wheel motor-generator set. However, for important hoists, the advantage of equalizing the input, and the perfect control possible with this type of apparatus more than compensates for the increased power consumption.

104. Converter balancing system. Another system has been devised, which provides for equalizing the input, but does not provide for the control of the hoist motor. This is shown in Fig. 11. In order to render the demand on the line constant, the equalizing system is connected in parallel with the generating station. It consists of a synchronous converter and a direct-current machine which is coupled to a suitable fly-wheel.

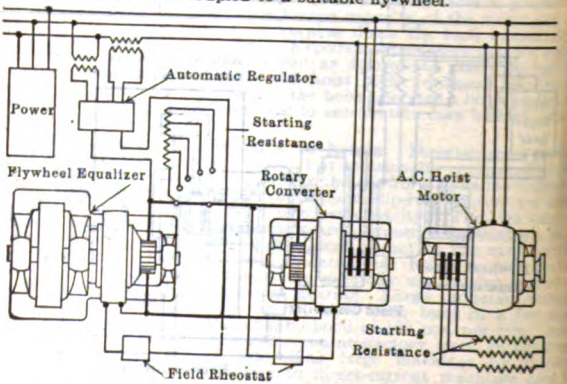


FIG. 11.—Converter balancing system.

105. Operation of the converter balancing system. The synchronous converter acts only as a connecting link between the alternating-current system and the equalizing set, which consists of a compound-wound direct-current machine coupled to the fly-wheel (Fig. 11). The field of this machine is controlled by a regulator, operated by a series-wound solenoid connected in the main-line. At the beginning of a trip the fly-wheel is running at full speed, and when the load current exceeds the mean value, the regulator automatically strengthens the field of the equalizing machine, so that it acts as a generator driven by the fly-wheel. The amount of energy delivered to the synchronous converter and thence to the line will depend on the excess of momentary load-current over the mean value of load current, for the regulator will continue to raise the excitation of the direct-current machine as long as there is any tendency for the line current to increase above the mean value.

When the current demand drops below the mean value, the regulator will weaken the field, thereby causing the machine to run as a motor, which, taking energy from the line through the synchronous converter, will accelerate the fly-wheel. As before, the rate at which the resistance is introduced in the field depends upon the excess of the mean current value over the momentary current demand. In this way energy is stored in the fly-

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momentarily.

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wheel and the line load is kept approximately constant. The synchronous converter changes either direct current to alternating current, or *vice versa*, depending upon whether the fly-wheel is delivering or receiving energy.

106. Comparison of Ilgner system with converter system. It will be seen that the fly-wheel speed variation in the converter method is obtained by field regulation of the direct-current motor, so that the loss is negligible. With the Ilgner system the loss is from 7.5 per cent. to 10 per cent. of the input to the driving motor. This is a very important feature in equalising systems using direct-current machines, as a much greater fly-wheel speed variation can be economically obtained with the converter method, it being the usual practice to allow from 20 per cent to 25 per cent., and consequently the fly-wheels can be comparatively light. The machines of the converter equalising equipment need be only large enough to deal with the load variations from the mean value, and under ordinary circumstances, the capacity need not be more than about one-half that of the motor-generator set for the same duty. The equalising equipment is quite independent of the hoisting motor, so that it may be out of service without cessation of hoisting. However, in this event the peak loads will be felt on the line. With the Ilgner system the hoist is directly dependent upon the motor-generator set.

107. Control for alternating-current motors. Magnetic-switch controllers are used to a considerable extent. Liquid controllers for the rotor circuit are also used, and these have the advantage of providing smoother acceleration and of being simpler in construction.

108. Types of switches in use. For the control of the primary, both oil and air-break magnetic switches are in use. For circuits of 550 volts and under ordinary magnetic switches are quite satisfactory. For 2,200-volt motors, special air-break switches are in use, and when properly designed are preferable to other types on account of the accessibility of the contacts and their ability to withstand hard service. Oil switches are used to a considerable extent but for very severe service they must be very liberally rated, otherwise there is danger of explosion, due to the heat generated in the oil. Drum controllers can be used only for small hoists requiring motors not larger than 75 h.p., and are not at all suitable for severe operating conditions. Magnetic-switch controllers can be used for all sizes, but liquid controllers are used only for motors of about 300 h.p. and above.

109. Control for direct-current hoist motors. Drum controllers are satisfactory for direct-current motors under 100 h.p., providing the service is not too severe. Magnetic switches should be used for motors above this capacity. Liquid controllers are not satisfactory for direct current. In cases of very large hoists with peak loads of 1,000 h.p. and above, rheostatic control, for either direct-current or alternating-current motors is not very practicable. When power equalisation is not required, a motor-generator set is used without a fly-wheel. In every respect the operation is the same as with the Ilgner system, except that the speed of the set is not varied. The efficiency of such an arrangement is often greater than that of the hoist with rheostatic control, and the maintenance is usually less than that of a large rheostatic controller, although the amount of apparatus involved is greater.

ELEVATORS

BY DAVID L. LINDQUIST

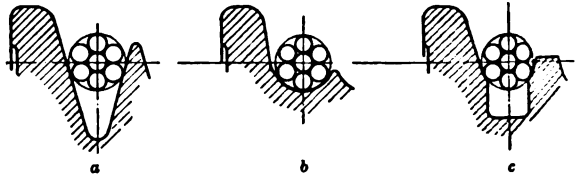
Chief Engineer Otis Elevator Company; Associate, American Institute of Electrical Engineers

110. Classification of electric elevators. There are two general classes of electric elevators, those employing grooved traction sheaves and those having spirally grooved drums. The cables of the former are frictionally driven by suitably grooved sheaves, while those of the latter are wound up on a drum to which they are positively attached. Traction type elevators are adapted to all kinds of elevator service, regardless of length of travel or car speed. They are frequently operated at 700 feet per minute and speeds of 1000 feet per minute are equally practical for high rise express service. Drum type elevators are limited to travels of about 100 feet and to car speeds of about 200 feet per minute. The general superiority of the traction

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type, particularly as to safety, has brought about the gradual elimination of the drum type, so that comparatively few drum elevator machines are now manufactured.

111. Grooving of drums and traction sheaves. Drums and traction sheaves with double cable wraps usually have semi-circular grooves as shown in Fig. 12(*b*). Traction sheaves with single-cable wrap usually have grooves of the V-section (Fig. 12*a*) or of semi-circular, under-cut section (Fig. 12*c*).



a *b* *c*

FIG. 12.

The circular groove gives the best support for the cable, *i.e.*, minimum pressure between sheave and rope, and consequently the least traction for a given arc of contact. To obtain sufficient traction it is usually necessary to resort to double wrap (Fig. 15) when round grooves are used. Sufficient traction can usually be obtained with a single wrap when the V or under-cut groove is used. In this case the secondary sheave shown in Fig. 15 is omitted.

The latter type of grooves gives, however, greater unit pressure between cable and sheave. This unit pressure is particularly high with a driving sheave of small diameter and steep angle V groove, which has not been worn. As excessive unit pressure will cause rapid wear of rope grooves as well as cables this matter must be given careful consideration particularly where plain V-grooves are used.

112. Roping and counterbalancing of elevators with winding drums. Necessary connections are usually made between drum and car and counterbalance by means of two ropes for each connection, thereby decreasing the size of ropes required, the increased flexibility permitting the use of small diameter drums and sheaves. Fig. 13 indicates the roping arrangement followed when a single or back drum counterbalance only is used; while Fig. 14 portrays similarly the arrangement necessitated by the use of a double counterbalance. With this latter arrangement, one counterbalance constitutes the back drum weight, while the other is attached directly to the car.

The total counterbalancing should be proportioned to the average load to be carried, which usually range from 30 to 40 per cent. of the rated maximum load. When only one counterbalance is used, therefore, its weight should equal that of the car plus from 30 to 40 per cent. of the maximum load in the car. With the double counterbalance, sum-total weight should also be equal to the weight of the car plus from 30 to 40 per cent. of the maximum load in the car. In this event, the counterbalance attached to the car is proportioned to approximately 70 per cent. of the actual weight of the car, the weight of the back drum counterbalance being equal to the difference between the total weight and that of the car counterbalance. Either method of counterbalancing imposes on the motor a net maximum load of approximately two-thirds the rated capacity of the elevator.

For car travels in excess of 100 ft. it is advisable to compensate variation in load on motor, produced by change in position of cables during run, by means of a compensating chain attached from the car to the middle point of the hatchway, as shown in Fig. 13, or attached from car to counter-balance as indicated in Fig. 14. The following formulas derive total compensating weight required, where h = weight of hoist ropes per ft.; dw = weight of drum counterbalance ropes per ft.; cw = weight of car counterbalance ropes per ft.; c = weight of compensating chain (or ropes) per ft. With compensating chain attached to car and middle point of hatch: $c = 2(h + dw + cw)$. With compensating chain attached to car and counterbalance: $c = (h + dw + 2cw)$. For installations employing the single counterbalance only; $cw = 0$.

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113. Roping and counterbalancing of elevators with traction heave. From Fig. 15, which clearly indicates roping required by what is nown as the 1 : 1 traction-sheave double-wrap type, it will be noted that he single length of ropes used are directly connected to car and counterbalance at either end. By the use of a secondary or idler sheave these ropes re passed over the traction sheave a second time as a means for increasing

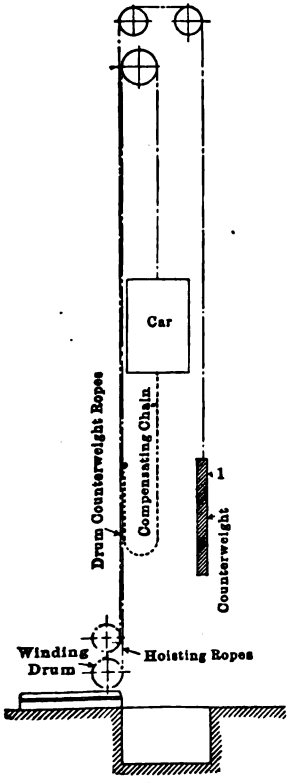


FIG. 13.—Roping arrangement for use with single (back drum) counter balance.

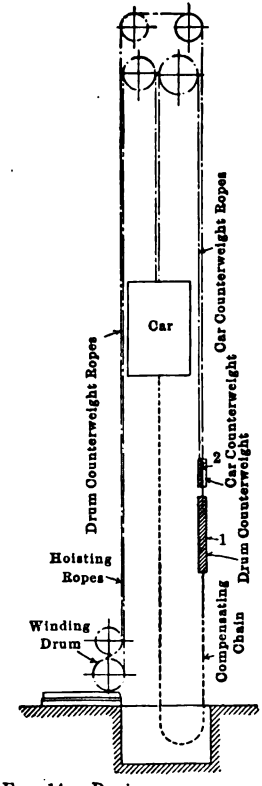


FIG. 14.—Roping arrangement for use with double counterbalance.

pe contact, which, under the influence of the combined weight of car and unterbalance, provides the adhesion requisite to elevator service.

The foregoing arrangement corresponds to that used for the 2 : 1 traction-heave type with the exception that the ropes, instead of being directly connected to car and counterbalance, are passed under traveling sheaves located the upper end of both car and counterbalance; from this point they are tended vertically to the top of the hatchway and there securely and permanently anchored. Fig. 16 represents the 2 : 1 roping arrangement.

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Both the 1 : 1 and 2 : 1 roping methods with double wrap, Fig. 15 and Fig. 16 respectively, may be used with single wrap having driving sheaves grooved as per Fig. 12*a* or Fig. 12*c* with the secondary sheave eliminated.

One of the striking advantages resulting from this arrangement of ropes and method of driving them, is the total loss of traction obtained if either car or counterbalance is obstructed in its descent, or bottoms on its respective oi

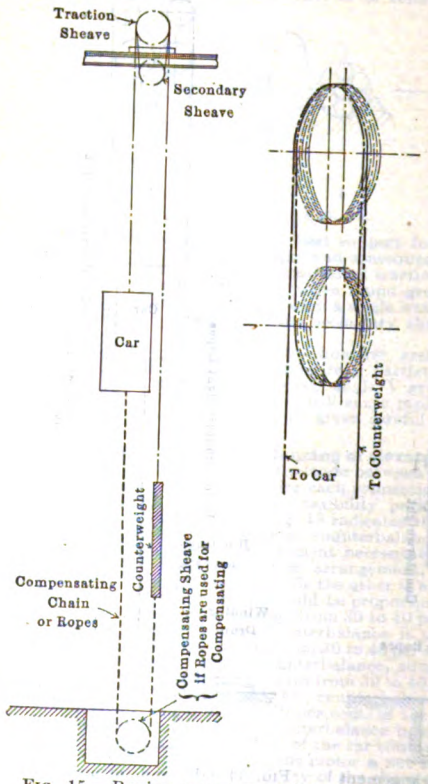


FIG. 15.—Roping arrangement for use with traction sheave.



FIG. 16.—Two to one roping arrangement.

buffer, causing complete cessation of all car motion even though the driving member may continue to revolve. This property of the traction-sheave elevator constitutes an extremely important and effective safeguard by enabling the absolute fixing of the car travel between two given limits, inasmuch as with proper roping the car will be brought to rest on its oil buffer before the counterbalance comes into contact with the overhead work and *vice versa*. A further advantage of the traction-sheave elevator lies in the fact that the faces of the sheaves are entirely independent of the height of the building.

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Counterbalancing must in all cases be proportioned for an equal margin of safety to counteract the tendency to slip on both up and down direction of travel under maximum load conditions. Where there is a considerable surplus of traction, however, the weight of the counterbalance should be made dependent upon the average loads in the car, which, for this type of elevator, usually range from approximately 33 to 45 per cent. of the maximum. Ordinarily, the total weight of the counterbalance should equal that of the car plus from 33 to 45 per cent. of the maximum load in the car.

Elevators with traction sheaves should in all cases be provided with rope compensation and with connections arranged in accordance with Fig. 14; the weight per hatchway ft. of the compensating ropes should equal approximately the weight of the hoist ropes per hatchway ft. minus one-fourth the weight per ft. of the electric control and lighting cables.

114. Electric elevator machines. The machines used for driving the two types of electric elevators mentioned are distinguished by their methods of power transmission between motor and winding drum or traction sheave, namely, (a) worm gear; (b) worm and spur gear; (c) helical or herringbone gear; (d) 1 : 1 gearless traction; (e) 2 : 1 gearless-traction machines. All of these machines should preferably be mounted over the hatchway although they can be located below where conditions demand.

115. Worm-gear machines. These machines are used for both passenger and freight service and may be arranged with either winding drum or traction sheave. For the smaller sizes, known as dumbwaiter machines, duties range from 500 lb. at 100 ft. per min. to 100 lb. at 500 ft. per min., while in the larger sizes the duties usually range from 500 lb. to 20,000 lb. and the speeds from 100 ft. to 400 ft. per min.

In order to preserve alignment, all parts should be assembled on a ribbed bedplate extending underneath the entire machine. The armature shaft of the motor is usually coupled direct to the worm shaft, the face of this coupling being utilized as the brake pulley. The worm and shaft should be solid and integral and of high-grade steel, the worm meshing with a bronze-rim worm wheel attached to a cast-iron spider. This spider, being directly and mechanically connected to the winding drum or traction sheave, renders power transmission at this point entirely independent of keys. Self-aligning ball thrust bearings are provided on the worm shaft.

116. Worm and spur-gear machines. The two types may be classified as safe lift machines and geared freight machines, the former being a special adaptation of the worm-gear machine when it is desired occasionally to lift loads greater than the normal and at considerably reduced speeds. This type is generally installed in office buildings, where, with the special arrangement applied to one or more of the ordinary passenger elevator machines, the handling of safes averaging from 4,000 lb. to 9,000 lb. in weight at a slow rate of speed, is greatly facilitated. To accomplish the increase in lifting capacity, a special provision is made for placing necessary gears in mesh between the armature and worm shaft, thereby reducing the car speed and increasing the lifting capacity in direct proportion to the ratio of the gearing inserted. By this method, therefore, and usually with a slight addition in counterbalance, the safe-lift loads are carried without requiring more current from the line than during normal operation. Geared freight machines differ from the worm-gear type by the addition of a single spur-gear reduction between the worm gear and the winding drum, thereby constituting them essentially slow-speed machines with relatively large lifting capacities.

117. Helical gear or herringbone gear machines. These machines, which can be arranged for use with either winding drums or traction sheaves, are provided with a single gear reduction to the motor by means of the helical or herringbone type of gear. Such gears permit a larger ratio of reduction with greater efficiency than can be obtained with ordinary spur gears. The motor speeds usually range from 300 to 600 r.p.m.

118. Gearless traction machines, 1 : 1 ratio. This machine represents a combination of extreme simplicity, maximum economy and highest efficiency. Briefly, it is a two-bearing electric machine, the armature, traction sheave and brake pulley being contained on the same shaft, all parts being compactly grouped on a cast-iron bed. The motor is of the plain shunt-field, slow-speed type of about 60 r.p.m. transmitting energy direct to the traction sheave. Contrary to general belief, these motors have remarkably high efficiency

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and a distinctive procedure has been to arrange design with a view to re
ing the highest efficiency (about 90 per cent.) at half rated capacity. T
figure corresponds with the average loads for this class of service, the f
load efficiency being approximately 87 per cent. Frequently these machi
are provided with ball bearings as a means for further increasing the efficie
and decreasing the space required.

Machines of this type should be located over the hatchway whenever i
at all possible. They are used for car speeds of from 500 to 800 ft. per m
with loads ranging from 2,000 to 4,000 lb. inclusive. To date only machi
employing direct-current motors have been produced.

By means of a special arrangement, the regular machines can be conver
so as to enable the lifting of safes weighing from 5,000 to 8,000 lb. T
arrangement includes the placing of a second magnet brake in operation
also the adding of extra weight to the regular counterbalance. When
ing safes, maximum field strength of motor is utilised, producing a prop
tionately slow car speed.

119. Gearless traction machines, 2:1 ratio. All mechanical feat
of these machines correspond to those of the 1 : 1 gearless-traction t
They have been designed for traction sheave elevators requiring lower
speeds than obtained with the 1 : 1 machine without the necessity of
reductions the car speed reduction being produced by the 2–1 roping arra
ment previously described. The machines have been designed for di
current service only, using shunt-field motors of from 80 to 140 rev. per
with resultant car speeds of from 250 to 450 ft. per min., and they have
installed for capacities up to 12,000 lb. By an arrangement similar to
with which the 1 : 1 gearless-traction machines are equipped, these mac
can also be used for safe lifting.

120. A common characteristic of all elevator motors is that the
must be specially constructed to withstand repeated stresses produced b
frequent starting and stopping. In general, however, the performance
alternating-current and direct-current motors differ to such an extent as n
necessitate their separate consideration.

121. Direct-current motors. This class of motors must be designed fo
sparkless commutation at starting, stopping and reversal of rotation und
all fluctuations of load within their rated capacity, and be capable of exertin
a heavy starting torque with minimum requirements as to starting curre
especially where frequent starts and stops are made, in order to reduce th
energy consumption and the reaction on the generating plant. Because
these requisite features, commercial motors are rendered generally unsui
able. As a means for reducing starting currents, those motors used fo
driving geared elevator machines, and usually operating at from 300 to 9
rev. per min., are arranged to start as compound-wound motors having
heavy series field which should be cut out, usually by a short-circuiting pro
ess, as the motor speed increases. At full speed, therefore, the mot
operates as a plain shunt-field type.

Because of the high self-induction of the field winding required by moto
used for driving the 1 : 1 and 2 : 1 gearless-traction machines, which general
operate at from 60 to 140 rev. per min., when at full speed, the fields a
connected permanently across the supply lines, with reduced current wh
machine is at rest; this procedure shortens the length of time required
bring the field to full strength on starting. Such a method of field conn
tion materially reduces motor starting current. For direct-current elevat
motors the starting torque required is usually double full-load torque wi
a starting current of about 125 per cent. of full-load current.

122. Single-speed polyphase slip-ring induction motor. This ty
of motor has been extensively used in the past for elevator service and to
certain extent is still used in the larger sizes.

123. Single-speed polyphase squirrel-cage induction motor. T
squirrel-cage motor has always appealed to the engineer for use in conn
tion with elevator drives, because of its simpler construction due to t
absence of slip rings, brushes and external resistance with its necessary sh
circuiting devices. Until recently motors of this type have been found m
or less unsatisfactory except in the smaller sizes because of their high st
ing current and tendency to overheat where the service was at all severe.
The squirrel-cage motor has, however, lately been very materially i

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proved. The principal improvements are the welding of the end rings to the rotor bars and the use of end rings of large radiating surfaces and very well ventilated. Such a design permits using a sufficiently high internal rotor resistance to reduce the starting current to about twice full-load running current and a smaller and consequently lighter rotor without objectionable temperature rise in severe service. Due to the fact that the modern squirrel-cage rotor has less momentum than a corresponding slip-ring rotor the starting torque required to start the complete elevator in a given time is less with the squirrel-cage motor. With less torque required and usually higher starting torque efficiency the squirrel-cage motor takes about the same starting current and power consumption as the slip-ring motor with its external starting resistance properly proportioned and short circuited in correct sequence and time.

With the poor attention that elevator controllers usually receive it is not surprising to find that in service a slip-ring motor frequently takes a starting current much greater than a corresponding size squirrel-cage motor and is sometimes stalled and burned out because the starting resistance happens to be left short-circuited or is short-circuited too rapidly.

For the purpose of preventing the starting current of the brake adding to the full starting current of the squirrel-cage motor, and also to give a smoother start, it is customary to insert momentarily at starting a certain amount of external stator resistance. While the squirrel-cage motor usually has a greater speed variation than the slip-ring motor with the slip rings well short-circuited, this disadvantage is more than offset by the increased reliability and safety. The squirrel-cage motor has a definite resistance, not materially altered, even if several rotor connections should become open, which is not likely to occur as these are welded.

With the slip-ring rotor there are several possibilities of getting excessive rotor resistance and even open rotor circuits since the rotor connections are usually soldered and connected in series. There also are possibilities of resistance grids breaking and brushes and bolted connections failing to make proper contact, as well as the failure of the starting device to short-circuit the starting resistance. It is obvious that when the load is sufficient to overhaul the motor, excessive or dangerous over-speed may occur when the rotor resistance is too high or the rotor circuits are open. Due to the simplification of both motor and control apparatus, increased reliability and safety, lesser first cost and maintenance, the squirrel-cage motor is, at the present time, in most cases considered preferable.

124. Two-speed polyphase induction motors. For car speeds of 150 ft. per min. and upwards it is advisable to use two speed motors and while it is possible to use motors of slip-ring type, having double windings both in the stator and rotor, better results are obtained by using here also motors of the squirrel-cage type with double windings in the stator. One stator winding is arranged with a number of poles corresponding to the high speed and the other winding for a larger number of poles corresponding to the slow speed. The high speed is usually three or more times the slow speed.

The control is arranged in such a way that the operator can run either on high or slow speed, but the motor will always start on slow speed and when practically full slow-speed is reached the slow-speed winding is automatically rendered inoperative and the high-speed winding is energized. In stopping from high speed, the high-speed winding is first rendered inoperative and the slow-speed winding is automatically energized and as soon as slow speed obtains the power is cut off and the brake applied. In changing from one speed to the other there should be no instant where the motor is without power with the brake released. One way to accomplish this is to connect the two windings in series and so arrange them that one or the other can be short circuited. This arrangement together with the use of a squirrel-cage rotor has practically eliminated the arcing at the controller contacts.

A single stator winding may be used by changing certain connections to give different numbers of poles but this requires a rather complicated switching arrangement, particularly as the power should not be interrupted while changing from one speed to the other.

125. Single-phase motors. Up to the present a type known as the repulsion-induction motor alone has proven successful and in sizes up to and including 15 h.p. These motors, which start as one of the repulsion type, are provided with a centrifugal governor, usually located within the

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armature core, so designed and adjusted that at about 80 per cent. of full speed the rotor winding is automatically short-circuited, and the motor operates as if it were of the simple induction type. These motors cannot be reversed while operating, as induction motors. Devices are required to prevent change of connections until speed has dropped below that point at which the repulsion connections are re-established in order that reversal of rotation may become effective. Although starting currents are comparatively high, this condition is not objectionable in the smaller sizes, and in the larger sizes the starting current may be appreciably reduced by an external resistance in the stator circuit so connected that it is effective at the moment of starting and during the first period of acceleration.

126. **Brakes.** All elevator machines are equipped with brakes for the purpose of assisting in stopping and holding the car securely at a landing under any and all conditions of loads up to and including the maximum specified. The brakes, which must be so designed as to be equally effective for either direction of rotation, generally consist of two separate and independent shoes, lined with leather or asbestos preparations, and actuated by heavy helical steel springs. Brake release should be obtained by means of an electromagnet, as this method enables the making of such connections that the brake will be instantly and positively applied on failure or interruption of current supply.

127. **Methods of control.** The controlling apparatus of an elevator constitutes one of its most important features, including devices for establishing direction, for producing proper acceleration, retardation, and speed regulation, and also including the necessary safety appliances. Usually slate panels bolted to floor standards are provided, the switches being mounted on its face with connections to these switches, and all resistances located on the rear. All contacts of the various safety devices are usually connected in circuit with the holding coil of what is known as a potential switch, and, since all current to the controller and machine is carried through the contacts of this switch, the operation of any one safety feature immediately interrupts all current to the equipment. This switch also constitutes a no-voltage circuit breaker and an excessive drop in voltage will cause the switch contacts to open. The motor circuits are completed by the reversing switches, two in number, one for the "up" and one for the "down" direction, respectively. The brake circuits are made simultaneously with the closing of either direction switch. In order to prevent conflict, reversing switches are generally electrically or mechanically interlocked.

128. **Automatic starting.** It is advisable, with direct-current elevators, to arrange the stepping-out of the armature starting resistance entirely independent of the operator, and by this process eliminate the damage which would result from a reduction of this resistance at too high a rate. As a means for reducing energy consumption, however, starting resistance should be stepped-out as rapidly as the load on the motor permits; this is accomplished by means of either series relay magnets or magnets dependent on the counter-electromotive force of the motor for operation. See article on "Motor Control" elsewhere in this section.

129. **Dynamic braking.** Except with the small-capacity machines, the wiring of direct-current controllers invariably includes a dynamic-brake circuit which is obtained by introducing a resistance across the armature terminals on stopping. The stopping field in some cases is obtained by having the shunt field (permanently in series with a limiting resistance) connected directly across the supply line. In other cases it is obtained by providing an extra low-resistance shunt field; in the smaller machines the residual magnetism of the field poles is sufficient. Although connecting the field permanently across the supply line slightly increases energy loss, an important safety feature is gained, for with such connections it becomes impossible to attain excessive car speeds either up or down should, for any reason, the machine brake fail to apply. By various methods stopping resistance is automatically stepped-out as the load on the motor permits, thereby strengthening the dynamic-braking effect. With two-speed alternating-current induction motors dynamic braking is obtained while changing from high to the slow speed. Usually no dynamic braking is provided in stopping from slow speed. As explained, single-speed alternating-current motors cannot readily produce a dynamic stop and the machine brakes must be relied upon entirely in bringing the car to rest.

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130. Elevator speeds. Direct-current elevators are generally arranged with one speed only for car speeds up to 150 ft. per min., except in the case of automatic push-button-controlled elevators which are provided with two-speed control for car speeds above 100 ft. per min. With car speeds above 150 ft. per min., two or more speeds, under control of the operator, are provided for convenience in making accurate landings. Alternating-current elevators are generally arranged for one speed only up to 150 ft. per min., except for automatic push-button-controlled elevators where two speeds may be used with car speeds exceeding 100 ft. per min. The foregoing applies with equal force to winding-drum and worm-gear traction-sheave machines, but where accurate stopping is essential two speeds may be provided with car speeds lower than those specified above. The methods of operation from the car are given in Par. **131** to **133.**

131. Car switch—magnet control. This method is suitable for all car speeds and consists of a master switch, located within the car, electrically connected to the operating coils of the magnetically actuated switches on the control panel. Connections are so arranged that after direction has been established the proper sequence of switches is obtained for the desired acceleration and retardation. The car switch should be so designed that it will automatically return to centre or stop position should the operator's hand, for any cause, be momentarily removed.

132. Automatic push-button control. By means of a special type of magnet controller, elevators can be operated by a selective arrangement consisting of a call button located at each floor and a series of buttons, corresponding to the floors to be served, located within the car.

133. Hand-rope control. The contacts of the reversing switches are operated by the revolving of a small sheave, to which they are directly or indirectly attached, the revolving of the sheave being accomplished by a pull on an endless rope connected to it and installed in the hatchway in order to be available from the car. For convenience this rope is occasionally connected to a hand wheel or revolving lever device located within the car. Hand rope control becomes difficult to manage as the speed of car is increased and for this reason is generally limited to car speeds below 150 ft. per min.

134. Automatic terminal stopping device. With machines of the winding-drum type this consists of a series of contacts usually located above the drum and positively operated either directly or indirectly by an arrangement on the extended drum shaft at the gear-case end. These contacts are so connected in the controller circuits that car speed is automatically reduced at predetermined distances from the terminal landings, and finally brought to rest approximately near either terminal landing, provided the operator, for any reason, has neglected to centre his controlling device.

Since with traction-sheave machines no fixed relation exists between the traction driving sheave and the position of the car in the hatchway, because of the creeping action of the hoist ropes, a machine-driven automatic terminal-stopping device cannot be used. With the worm-gear traction-sheave elevators it has become the practice to locate a series of switches in the hatchway, properly spaced, operated by a cam mounted on the car, for producing the necessary slow-down and stop at the terminal landings. Because of the increased number of speed-reducing steps required with the higher-speed gearless traction-sheave elevators, the switch arrangement in the hatchway would present wiring complications and increase the difficulty of adjustment, and for this reason it has become advisable to carry the switches on the car completely enclosed in a metal case for protection, operated by one cam located at the top and one at the bottom of the hatchway.

135. Slack-cable switch. This device is used with winding-drum elevators only for the purpose of stopping the machine and preventing the unwinding of hoist ropes in case the car is obstructed in its descent. The contact of the slack-cable device is connected in series with the holding coil of the potential switch or circuit-breaker which, on opening, interrupts all current to the machine. Slack-cable switches are not required with traction-sheave elevators for, as previously described, the obstructing of either car or counter-weight immediately causes sufficient loss of traction to prevent further motion of the car and counterbalance.

136. Final hatchway-limit switches. To guard against the possibility of damage through disarrangement of the automatic terminal-stopping

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device, final limit switches are located, one each, beyond the terminal landings, and are operated by a cam on the car, in case the car overtravels to a point at which these switches become operative. The contacts of these switches are also placed in series with the holding coil of the circuit-breaker, causing immediate interruption of current to the machine when opened.

137. Governor switches. With high-speed elevators, regulating devices are usually provided, these being operated by a speed governor. These devices control car speed by means of field regulation of the motor, and are usually applied when the car speed exceeds normal by certain predetermined amounts. One or more speed-regulating switches are used, the number depending upon the average speed of the car, and, by their use, maximum speed variation is retained within certain predetermined limits. Governors should preferably be provided with a breaking contact adjusted to open at a car speed slightly lower than that at which the car safeties are set to operate. Therefore, connecting this contact in series with the holding coil of the potential switch or circuit-breaker, usually stops the elevator by interrupting all current to the motor, without the necessity of applying the car safeties.

138. Car safety switch. All electric elevators should be provided with a small enclosed switch, located within the car and so connected in the control circuits that current to the machine will be interrupted when it is opened. This switch is furnished for emergency purposes only.

139. Car-safety devices. The expression "car safety" is usually applied to that form of safety which is designed to bring the car to rest by locking it to the guide rails, in case excessive speed has been attained, irrespective of the cause. All elevators should be equipped with a device of this nature. The application of car safeties should be made dependent upon an a centrifugal or inertia governor, adjusted with a definite and fixed relation to the speed of the car and arranged to operate at approximately from 30 to 50 per cent. above normal car speed. The general practice is to support the safety device within the lower member of the car frame, with the governor substantially supported at the top of the hatchway, although, in some cases, specially designed governors are mounted on the car. With the governor located over the hatchway, it is driven by an endless rope attached to the car and safety mechanism in such a manner that, in case of excessive speed, the governor holds or grips this rope and the safety is applied, usually by means of a drum, sheave or lever arrangement.

Under certain building conditions, namely: where a room or vault is located directly underneath the hatchway, it is advisable to furnish a guide grip safety for the counterbalance as well as for the car, in order to prevent damage such as might otherwise occur through the breaking of the ropes. On all of the recent higher class installations counterbalance safeties have been furnished even where the foregoing condition has not existed.

140. Micro-leveling elevators. The micro-leveling elevator is one capable of giving automatically any desired accuracy of landing, irrespective of the load and speed. It is intended for use wherever level landings are desired and is particularly applicable where it is necessary not only to make but also automatically maintain accurate landings during loading and unloading, independent of the stretch of the hoist ropes or leaking pistons. Where conditions necessitate that the car be brought to rest against a solid abutment, as is usually the case with double cage elevators or inclined hoists, a landing can be effected without shock or injury to any part of the apparatus.

Micro-leveling elevators can be made for any load, any speed, any kind of motive power and for any type of hoisting machine and method of control. Up to the present time only the electric and hydraulic types have been built.

141. Electric micro-leveling elevators. The electric micro-leveling elevator embodies two essential parts, consisting of the main hoisting machine and the micro attachment. The main hoisting machine, with the exception of the magnet brake, may be of any type and involves no special features. The main brake is usually of the regular shoe type except that the housing instead of being bolted to the bedplate is fastened to the worm gear of the micro and revolves with it. This main brake performs a double function. First, with the micro at rest it acts as a brake to stop the main machine and second, when the micro operates it acts as a friction clutch driving the main machine. The micro is in itself a small elevator machine consisting of motor, brake and worm gear reduction.

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With the micro-leveling machine there are two controllers, one to control the operation of the main motor and the other to control the operation of the micro motor. The main controller is operated in the usual manner, either by push button, car switch or mechanical control (hand rope, lever or wheel). The micro controller is operated by a leveling switch mounted on the car frame. This leveling switch consists of two sets of contacts which control the micro motor, one for up and the other for the down direction. These contacts are operated by stationery cams in the hatchway, there being two cams at each landing, one of which operates the up contacts and the other the down contacts.

As the car approaches the landing at which it is intended it shall stop, the circuit of the main motor is interrupted by either the floor controller, car switch or mechanical operating mechanism, and the leveling switch engages the hatchway cams thus operating the micro motor. If the main machine brings the platform either above or below the landing, the micro will then raise or lower it until it is level with the landing, when the leveling switch will interrupt the circuit of the micro motor and stop the car. This position of the platform will now be maintained under all conditions of loading,

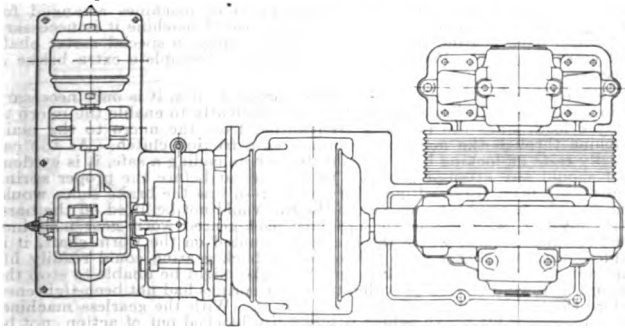


FIG. 17.—A. C. micro-drive elevator machine.

as the automatic control of the micro motor is independent of the door or gate contacts; *i.e.*, if the position of the platform be changed either by increasing or decreasing the load, the micro will immediately return it to its proper level.

There are two types of leveling switches. One for use where there are top and bottom landings only and the other for use where there are intermediate landings. With the top and bottom landings only, the leveling switch is so arranged that as the car approaches the upper landing it will engage the cam at this landing and while the car approaches the lower landing it will engage the cam at that landing. Where there are intermediate landings it is necessary to prevent the leveling switch from engaging the hatchway cams at these landings as the car passes them at full speed. This is accomplished by means of a magnet mounted on the switch, which, when the car is being operated from the main motor, prevents the leveling switch from engaging the cams. When the power is cut off from the main motor this magnet is de-energized and if the car is in the micro zone the leveling switch will engage the cam. The accuracy with which the platform stops relative to the landing depends upon the location of the leveling switch on the car and the setting of the hatchway leveling cams.

To obtain the greatest degree of accuracy the leveling switch should be located in a vertical plane through the edge of the platform it is desired to level, thus eliminating any slight misalignment caused by the deflection of the car structure and lost motion between the car and guides. The maximum micro zone is determined by the length of the leveling cams and varies with the speed, control system and service. The actual micro zone is the space in which the micro-drive operates.

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For push-button control the actual micro zone is determined by the setting of the floor controller and the adjustment of the dynamic and mechanical brake of the main machine. The floor controller should, therefore, be set so that with the average load it will stop the main machine when the platform is level with the landing. For car switch and mechanical control the actual micro zone depends entirely upon the operator. It is, of course essential that the operator brings the car within the maximum micro zone otherwise no micro operation will be obtained. In all cases the actual micro zone should be as short as practicable in order to save time in leveling. With a push-button machine where the actual micro zone is comparatively large, it is preferable to use a two-speed micro which will permit of the car being brought close to the landing at fairly high speed and the final leveling done at the slow speed required for an accurate landing. For the purpose of saving time it is also preferable to use a two-speed micro for high-speed car switch control machines and also on machines of moderate speed where great accuracy of landing is required.

142. Safe lift operation. The micro-leveling elevator either of the worm geared or gearless type is readily used for safe lifting and when so used has several advantages over other types of machines arranged for the same purpose. For the ordinary worm-geared machine it is necessary to furnish back gearing with its shaft and bearings, a special motor shaft and extra coupling. For the gearless machine a complete extra brake is necessary.

To use the micro-leveling elevator for carrying safes, it is only necessary to increase the main brake spring tension sufficiently to enable the micro to lift the load, since the power is transmitted from the micro to the main machine through the main brake acting as a friction clutch. As the car usually rests on locking bars while loading or unloading a safe, it is evident that should any attempt be made to lift the car before the proper spring tension has been obtained, no injury could result as the brake shoes would simply slide on the brake wheel and the car would not be lifted off the bars.

If, however, we consider the ordinary back-geared worm-gear machines used for lifting safes, where the brake is mounted on the worm shaft, it is evident that the motor acting through the back gearing could readily lift the car containing the safe, although the brake might be unable to stop the car in the down direction provided the brake springs had not been tightened before the car was lifted off the locking bars. With the gearless machine, should the safe lift brake, which is ordinarily blocked out of action, not be thrown into service, it will be impossible to stop the car by the brake and it will accelerate until stopped by the safety or the buffers.

143. Hydraulic micro-leveling elevators. The hydraulic micro-leveling elevator with electrical micro control consists of two independent operating devices which may be termed the main operating mechanism and the micro-operating mechanism. The former is operated by push button, hand rope or lever device, while the latter is operated in the micro zone after the main valve has been centered. The main machine may be of any of the recognized types of hydraulic machines.

The micro-operating mechanism consists of a micro valve which regulates the supply and discharge of water to the hydraulic cylinder through a by-pass around the main operating valve and is controlled by two electro-magnets. The control system for operating the micro valve is essentially the same as for the electric micro-leveling machine, having a leveling switch mounted on the car frame engaging the leveling switch cams at each landing. This switch controls the magnets operating the micro-pilot valve, which brings the car level with the landing and maintains it there.

144. General features common to both electric and hydraulic micro-leveling elevators. Since the car is leveling at micro speed during part of the time that the hatchway doors and car gates are being opened, suitable precautions must be taken for the protection of passengers attempting to enter or leave the car during that period. The depth of the platform at landing edge plus the depth of the landing sill must be greater than the length of the micro zone or it should be made impossible to open the hatchway door while either the upper edge of the car platform is below the lower edge of the landing sill as the car approaches the landing from below or the lower edge of the car platform is above the upper edge of the landing sill as

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the car approaches the landing from above. In other words, it must be made impossible for a person to get his foot between the landing sill and the car platform.

145. Micro-emergency operation. An emergency operation can be furnished with any system of control. This consists of two extra push buttons installed in the car, one for operating the car by the micro in the up direction and one for the down direction.

146. The number of elevators required in a building depends on several conditions, namely: height of building, relation of area of building to its height, net rentable area in sq. ft. per floor, character of elevator service required by prospective tenants and relative location of building. In average office buildings it is not considered good practice to attempt to serve

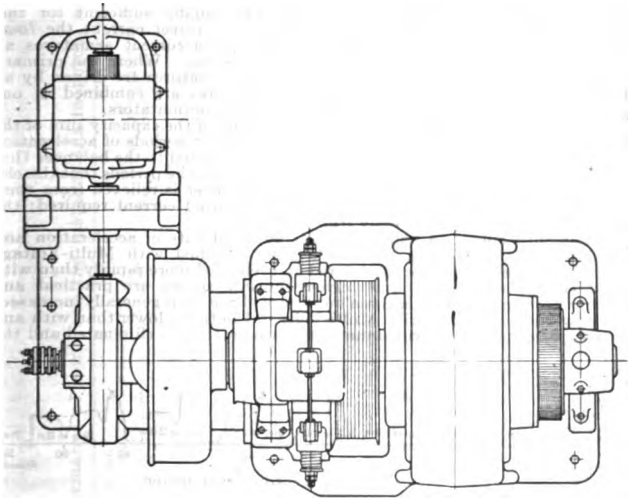


Fig. 18. – D. C. micro-drive elevator machine.

more than from 18,000 to 24,000 sq. ft. of rentable floor area per elevator. The mileage of each elevator in a modern office building ranges from 15 to 40 miles per day, depending on the character of service and type of elevators used. These are general figures only, and complete service data must receive detailed consideration to accurately specify the most suitable elevator equipment for a given installation.

147. General consideration of energy consumption. Usually, it is safe to assume that the loads distributed by an elevator to the different floors of a building are the same, approximately, as those loads returned to the starting point, and with such load conditions the work done consists merely of overcoming the friction. Of greater importanee, therefore, in the energy consumption, is the power expended in imparting the kinetic energy required to bring the masses up to speed, and the machine which will register the lowest power consumption must have a low moment of inertia together with a low value of friction.

The machine at present fulfilling the foregoing requirements to the most satisfactory degree, is the 1 : 1 gearless traction-sheave machine and this fact is clearly evidenced by the following comparison between a 1 : 1 traction machine with motor running at 74 rev. per min., and a herringbone-gear traction-sheave machine driven by a 600-rev. per min. motor, both of

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these machines being designed for a lifting capacity of 2,500 lb. at a speed of 700 ft. per min. It was found that the kinetic energy required to bring the 1 : 1 traction machine up to speed, without the car, counterbalance or ropes, was 3,600 ft-lb., while, under the same conditions, the herringbone-gear traction machine required the expenditure of 17,900 ft-lb. in attaining full speed. The total number of starts and stops of an elevator constitute an important factor in the resultant power consumption per mile of car travel, because of resistance losses which are greatly increased with increased kinetic energy.

148. Multi-voltage system. This system, as applied to electric elevators, usually results in a very considerable reduction of power consumption as well as better and smoother operation. The voltage is divided into equal steps successively applied to the motor without any external armature resistance. Four voltage steps are usually sufficient for this purpose. Where the primary source of power is direct current the four-voltage steps are obtained by floating four direct-current armatures all mechanically connected and in series across the line. Where the primary source of power is alternating current the four armatures are driven by an alternating-current motor. Usually two armatures are combined in one armature having two separate windings and two commutators.

This Multi-Voltage Balancer has only a fraction of the capacity sum of the elevator motors supplied by it during a part of their periods of acceleration and retardation. The elevator motors are so connected to the balancer that half of them start from each side of the line. During the periods that the elevator motors are connected to the line, the balancer is relieved from the loads, and only supplies at any time the unbalanced current required; the balanced current coming directly from the line.

The smooth operation and practically constant rate of acceleration and retardation with all loads, of the elevators supplied with Multi-Voltage Control, enables them to be accelerated and retarded more rapidly than with single voltage control, so that higher elevator speeds are practical and the service obtainable from a given number of elevators is generally increased. The power consumption with Multi-Voltage Control is lower than with any other type, since external resistance losses are practically eliminated and the

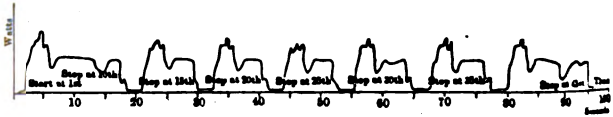


FIG. 19.—Graph of recording wattmeter.

continuous running equipment is reduced in a minimum. It is decidedly superior to the Ward-Leonard system in economy and in amount of special generating equipment necessary. Multi-Voltage Control requires only a single balancer having a small fraction of the capacity sum of the elevator motors supplied. Ward-Leonard control requires an individual generator of full capacity for each elevator motor. The Ward-Leonard equipment must also carry the full current of the elevator motors for a much larger percentage of the running time than the multi-voltage balancer and, as usually arranged, carries all the current supplied to the elevator motor armatures while they are running. Thus, both constant and variable generating losses are higher for Ward-Leonard than for Multi Voltage Control. Ward-Leonard control is also handicapped by requiring large field variation in the special generators. It is not only difficult to design the apparatus to allow the field to be changed with sufficient rapidity, but it is also necessary to provide special devices for commutation.

149. The line to load efficiency is determined by ascertaining the total electrical input, and the net work done on the load.

150. Required power is best determined by means of a recording wattmeter writing a graph which shows the existent relation between watts and time, the energy consumption in kw-hr. being represented by the area surrounded by the graph and the axis of time. Fig. 19 is a reproduction of such a graph taken in one of the largest office buildings in New York City.

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151. The average performance of some existing installations in actual service

Machine type	Specification		Rise	Class of service and building	Energy cons. kw-hr. per car mile
	Control	Maximum lifting capacity			
Worm-gear and drum...	Magnet, direct current	2,000 lb. at 300 ft. per min.	140 ft.	Hotel, passenger service	3.3
Worm-gear and drum...	Magnet, direct current	1,500 lb. at 275 ft. per min.	113 ft.	Small building, passenger service	2.35
Worm-gear and traction-sheave	Magnet, direct current	3,000 lb. at 300 ft. per min.	165 ft.	Large department store passenger service, stop at each floor	8.71
Worm-gear and traction-sheave	Magnet, direct current	3,000 lb. at 300 ft. per min.	170 ft.	Small office building passenger service	5.1
1 : 1 traction.....	Magnet, direct current	2,500 lb. at 550 ft. per min.		Large office building passenger service. Local service from 1 to 14 only.	4.0
				Express service from 1 to 25—no stops below 15.	2.85
2 : 1 traction.....	Magnet, direct current	3,000 lb. at 450 ft. per min.		Small office building passenger service	3.91

All of these readings are for direct-current elevators only. From 20 to 30 per cent. more power consumption will be required by alternating-current elevators under the same conditions.

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152. Influence of number of stops on energy consumption
(*Test data*)

Specification type of machine and control	Load in car	Average speed, ft. per min.	Number of stops between terminal landings per mile of travel	Energy cons. in kw-hr. per mile of travel	Running efficiency (line to full load)
Worm-gear drum machine Direct-current motor Magnet control Duty Maximum load 2,500 lb. 2,000 lb. at 300 ft. per min. Rise, 69 ft. 6 in. Overbalance 650 lb.	2,150	326	0 76 152 380	2.04 3.31 4.33 7.34	56.0 per cent.
	1,350	320	0 76 152 380	1.48 2.47 3.35 6.21	
1 : 1 traction direct duty motor Magnet control Duty 2,500 lb. at 600 ft. per min. Rise 537 ft. 0 in. overbalance 1,125 lb.	1,500	600	0 50	1.15 2.45	68 per cent. with maximum load.

153. Testing of electric elevators. When an elevator is completed the usual test consists of carrying the rated load at full speed, setting the car safety by overspeeding, and a trial operation of all electrical or mechanical safety features to determine their effectiveness. A more complicated test comprises determinations as to friction, line to load efficiencies with different loads in the car, the energy consumption with various net loads on the motor and number of stops, and the speed characteristics and the kinetic energy.

154. Energy calculations. As previously explained the kinetic energy W required to accelerate the masses of the speed V has an important bearing on the power requirements. Its determination is made accurate and comparatively simple by application of the formula:

$$W = \int_0^T fv\delta t = 0.7373 \int_0^T P_v \delta t \qquad \text{(watt-sec.)} \qquad (2)$$

in which f is the accelerating or retarding force in lb. and v the velocity in ft. per sec. at the time t. T is the total time in sec. for the body to come to rest from velocity v.

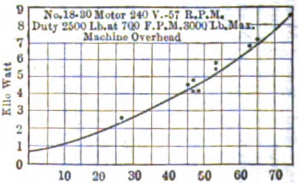


FIG. 20.—Watt input—speed curve.

In the foregoing formula fv represents the work per sec. performed by the accelerating or retarding force, and is equal to 0.7373 P_v if P_v is expressed in watts. Consequently P_v represents the accelerating or retarding watts at the speed v and time t, and the quantity under the integral sign is the area contained between the accelerating or retarding watt-time curve and the axis of time. This curve is readily obtained, for if sufficient load be placed in the car so that the weight on the hoist ropes equals the weight on the

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counterbalance ropes, the watts input into the armature necessary to drive the elevator at the speed v, minus the I^2R losses, must equal the retarding watts, if, at the speed v, the armature current be interrupted.

Under this method, a watt input-speed curve, Fig. 20, is first secured, following which a retardation curve, Fig. 21, is obtained; this latter curve is a speed-time curve giving the relation between speed and time if, at the speed r, the armature circuit is interrupted and the elevator system allowed to

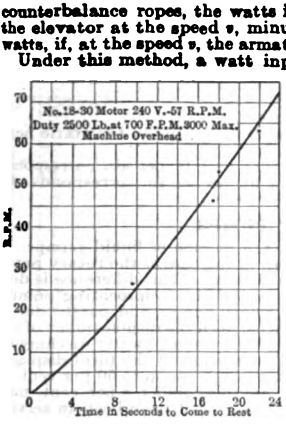


FIG. 21.—Retardation curve.

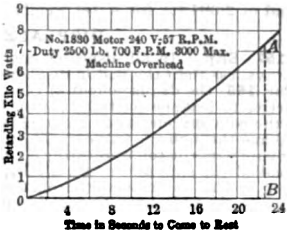


FIG. 22.—Retarding watt-time curve.

come gradually to rest. From these two curves the retarding watt-time curve, Fig. 22, is constructed and the area obtained with a planimeter. The retarding watt-time curve is practically a parabola, and an inappreciable error is made by considering the curve as such. Instead of obtaining the area with a planimeter it is permissible to use that property of parabolas by which the area OAB Fig. 22 is equal to one-third the product of AB into OB.

POWER PUMPS

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GENERAL

155. Classification of power pumps. Power pumps for all practical purposes can be divided into two general classes—displacement pumps and centrifugal pumps. Displacement pumps may be further divided into reciprocating pumps and rotary pumps, while centrifugal pumps may be divided into turbine and volute pumps. As will be shown later, the two classes of displacement pumps differ radically in design and are really distinct classes, while the difference between turbine and volute pumps is a difference of detail of construction, rather than a difference of type.

156. Calculation of the horse power required, is based upon a consideration of the opposed head (expressed in ft. or lb. per sq. in.) the pump delivery (expressed in gal. per min. or cu. ft. per sec.); and the efficiency of pump and mechanical transmission. Pump efficiencies vary with the different types, sises, and working conditions. See Par. **161, 164, and 172.**

The head will include the static head pumped against and also the head of pipe friction. A calculation of required horse power should always consider the latter component of total head if the pipe is of considerable length. **Friction head** may be calculated with reasonable accuracy by means of Eq. 3. Accuracy within 6 per cent. may be expected for new, smooth pipes, while accuracies within 20 per cent. may be secured by its use on practically all pipes met in common practice. This expression is a modification of the well-known "Exponential" formula for straight smooth pipe.*

$$h_f = 1.6\,\frac{G^{1.87}}{d^5}\left(\frac{L}{1{,}000}\right) \qquad (3)$$

* Moritz, E. A. *Eng. Record*, Dec. 13, 1913.

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where G is the delivery in gal. per min.; L is the total length of the pipe in ft.; d is the inside diameter of the pipe in in.; and h_f is the friction head, expressed in ft., for the *whole* pipe length. The horse power required to pump a certain quantity of water through a given length of pipe of known diameter against a given head is expressed as follows:

$$\text{h.p.} = \frac{G \times H}{3{,}950 \times \text{Efficiency}} \qquad (4)$$

where G is the delivery in gal. per min., and H is the sum of the static head and the friction head, both expressed in ft.

In using these formulæ it is well to note that 1 cu. ft. per sec. corresponds to 448.8 gal. per min.; also a pressure of 1 lb. per sq. in. corresponds to a head of 2.304 ft., for water weighing 62.5 lb. per cu. ft.

DISPLACEMENT PUMPS

157. Slip. In all displacement pumps, the volume of liquid pumped is always less than the piston displacement, or, in the case of the rotary pump (Par. 163) the displacement of the rotating element. This difference is due, partly, to leakage past the piston (in the case of the reciprocating pump), or the rotating element (in the case of the rotary pump), and partly due to leakage through the valves. The difference between the displacement of the moving part (piston or rotating element) and the volume of water discharged, is called the slip, and is usually expressed in per cent. of the total displacement. This slip may vary from 2 per cent. in a new pump to 50 per cent in a badly worn pump. Generally speaking, anything under 5 per cent. may be considered fairly good performance for pumps that have been in service any length of time.

158. Effect of speed on capacity of displacement pumps. Neglecting slip, the capacity of all types of displacement pumps varies directly with the speed, regardless of the head pumped against. For constant head, the horse power required varies almost directly as the speed and, therefore, as the capacity. This, of course, is not strictly true, for the pump efficiency will be slightly greater and the slip in per cent. slightly less as the pump approaches rated capacity. These characteristics and the service to be performed will determine the type of motor to be installed.

159. Displacement pumps under constant head require practically constant driving torque at all speeds and, therefore, at all capacities. This characteristic has a very direct bearing on the type of motor to be selected in cases where it is required to operate the pump at variable capacity and, therefore, at variable speed. From this, it is evident that no saving of power will result if variable speed of the pump is obtained by inserting resistance in the armature circuit of a direct-current motor, or in the rotor circuit of an induction motor. To effect a saving of power, it is necessary to use field control, in the case of the direct-current motor, or a pole-changing device for an alternating-current motor, or any similar device in which the torque of the motor remains constant, for reduced power consumption at the motor service switch. In considering the question of head, it should be kept in mind that the total head on a pump includes both the static head and the friction head in the pipe connections. Where this friction head constitutes a large proportion of the total head, another factor must be taken into consideration. The velocity in the discharge pipe varies directly with the quantity discharged, while the friction head varies as the square of velocity, consequently a pump under these conditions, running at reduced capacity, will not be discharging against a constant head, even though the *static* head is constant, but instead, the head against which the pump operates will be less at partial loads.

160. Starting torque of displacement pumps. Displacement pumps operating at constant speed against a variable head will have a constant rate of discharge. The torque and horse-power input will vary (neglecting minor losses) directly with the head. In starting these pumps against the normal working pressure, the motor must exert full-load torque. As this requires very heavy starting currents, especially in the case of induction motors, the expedient of by-passing the pump in starting is usually employed wherever this is practicable. Where the by-pass is installed, the head at starting, and therefore the starting torque, can be reduced to a negligible quantity. After the pump is up to speed, the by-pass is closed.

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161. The efficiency of reciprocating pumps is generally higher than the efficiency of any other type of pump for the same service. This assumes the pump to be in good condition and the slip comparatively small. The curves in Fig. 23 illustrate the efficiency that can reasonably be expected of triplex pumps of good manufacture. It should be understood that these curves do not represent the performance of a single pump, but rather the efficiency of a series of pumps, each designed for a particular point on that curve, or for a given capacity and head. These pumps are ordinarily designed to operate at a piston speed of from 30 ft. per min., for pumps of 6-in. stroke, or less, to 75 or 80 ft. per min., for pumps of 16-in. stroke or over. These low piston speeds, in turn, require extremely low shaft speeds, as compared with the ordinary motor speeds. This condition is met by installing a slow-speed motor with belt or silent-chain drive, by a double gear reduction, or by a combination of the two. This reduction in speed, especially when accomplished by the double gears, necessarily involves a considerable loss of power, and this loss should be considered in comparing pump efficiencies. The efficiency increases with the capacity of the pump, for the same reason that the efficiency of similar pieces of apparatus increases with the size.

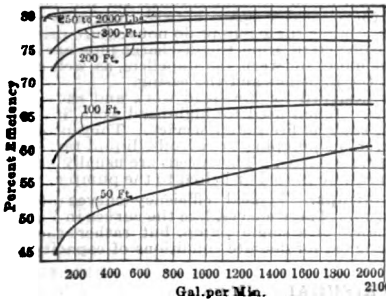


FIG. 23.—Efficiency curves of triplex pumps under various heads.

162. Reciprocating-pump types. Most displacement pumps are of the reciprocating type. In very small sizes, they are generally single-cylinder pumps, while in the larger sizes they are more frequently triplex pumps. While most manufacturers of this type of pump build duplex pumps, the latter have not found favor to the same extent that the other two types have. All simplex, duplex and triplex pumps are built in both the single-acting and double-acting pattern, *i.e.*, built to discharge only during one stroke of each revolution or during both strokes. It should be noted that in the case of the **single-acting pump**, the simplex pump gives one impulse, the duplex two and the triplex three impulses per revolution, while in the case of the **double-acting type**, the simplex gives two, the duplex four and the triplex six impulses per revolution. Where uniformity of discharge and absence of pulsations is of primary importance, this feature will have a very direct bearing on the type of pump selected.

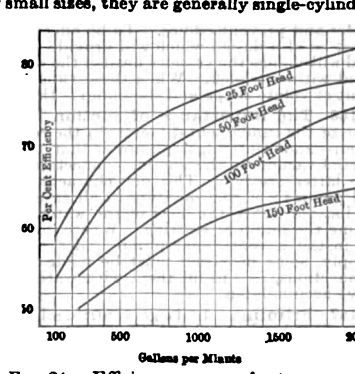


FIG. 24.—Efficiency curves of rotary pumps under various heads.

163. Rotary pumps in their essential parts consist of two rotating elements, sometimes called impellers or cams, enclosed in a casing. These

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two elements "mesh" in much the same manner as a pair of gears, bearing on each other in line contacts. Consequently, any wear that occurs cannot be compensated for by packing or by adjustment of the moving parts. The slip in this type of pump is caused by the leakage through the line contact of the impellers and through the clearance space between the ends of the impellers and the pump casing. While these pumps do not require priming, they frequently have a small connection from the discharge pipe back into the pump casing to "seal" the joints between the impellers, as well as the small clearance space between the impellers and the casing.

These pumps are primarily designed for low-head work and show their greatest efficiency at low heads. When used for high-head work, it is generally for intermittent service, such as fire-pump service. They probably find their greatest field, however, in pumping heavy oils, liquid tar, syrup, and liquid food products of various kinds. The speeds are usually so low that motors of ordinary speed must be geared or belted to the pump shaft.

164. Efficiency of rotary pumps. Typical efficiency curves of this type of pump are shown in Fig. 23. These curves, like the curves in Fig. 23, do not represent the performance of a single pump, but rather the efficiencies of a series of pumps, designed for definite conditions of capacity and load, plotted in a single curve.

CENTRIFUGAL PUMPS

165. Mechanical construction. Centrifugal pumps for low heads are almost always of volute type, but manufacturers and designing engineers apparently differ as to the best practice to be followed for pumps discharging against higher heads. The turbine and the volute types of pump use substantially the same type of impeller. The difference between the two types lies in the design of the water passages of the casing. The volute pump, as its name implies, has these water passages built in the form of a volute, increasing in size toward the discharge opening. For the lower heads, the velocity of the water is comparatively slow and there is little or no "churning" and "eddying." Moreover, as this type of pump is cheaper to build than a turbine pump, the reason for its popularity for low heads is evident. For higher heads, however, the velocity in the pump casing is necessarily great, and this increases the tendency to form eddies with resultant loss of efficiency. To meet this situation, some builders resort to diffusion vanes. These vanes are a part of the pump casing and simply act as guides to direct the flow of the water and prevent eddies. To be effective and not cause loss of head, they must be of a design which will provide water passages with long easy curves and will change the velocity head of the water leaving the impeller, to pressure head without shock. When these vanes are added, the casing is no longer built of volute shape and the pump is then called a turbine pump.

166. The importance of suction lift in the selection of a pump. One of the fundamental factors in the relative performance of displacement pumps and centrifugal pumps is that the former are capable of creating a partial vacuum in the suction connection without priming (Par. 167), while the latter are not. This one characteristic at once eliminates the centrifugal pump from consideration in all cases where the pump must necessarily be located above the level of the water, and where it is not practicable to prime the pump at starting. Where, for other reasons, it appears desirable to install a centrifugal pump under conditions where it must "lift" its supply, some provision must be made to prime the pump and its suction connections, *i.e.*, to fill them with water and expel all of the air that may have accumulated.

167. Priming. In large centrifugal pumps, this priming is usually accomplished by actually "lifting" the water through the suction pipe and the pump from the source of supply by some auxiliary device. Where steam is available, a steam syphon is a very satisfactory means of accomplishing this result. Where condensing apparatus is used, the water may be "lifted" into the pump by means of a connection from the vacuum chamber of the condenser to the pump casing. Where no such auxiliary devices are available or their installation impracticable, a hand pump may be installed. In the case of small pumps, this result is usually accomplished by installing a check valve in the suction line or, better still, a foot valve at the bottom of the suction line. In addition, a "priming" connection is made to some available supply so that by opening the valve or connection, the pump and

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suction line are filled with water, a vent cock being usually provided in the top of the casing to allow the escape of air while the pump and suction line are being filled. The pump is then started, but *not* until the suction line and pump casing are entirely filled with water. Once the pump is in operation, it will continue to pump with practically no danger of losing its priming, unless the suction lift becomes abnormally high or air leaks into the suction pipe or pump casing.

168. Attainable suction lift. With all air leaks eliminated, almost any good centrifugal pump may be depended on for a suction lift of 15 ft. (after it has been primed and started). Under favorable conditions, this may be increased to 20 ft. suction lift. While there are centrifugal pumps operating under greater than 20 ft. suction lifts, this requires the best of conditions, both as to pump and connections, and even then it must be understood that these same pumps would be much more reliable and dependable if the suction lift were reduced to 20 ft., or less. This same characteristic makes a centrifugal pump much more sensitive to air leaks in the suction connection than a displacement pump. An air leak in the suction line of a centrifugal pump which is not even sufficient to cause a displacement pump to "knock" may cause a centrifugal pump to "lose its suction" or "priming."

169. Multi-stage pumps. A pump designed to deliver 100 gal. per min., against a head of 75 ft., will require exactly the same h.p. to deliver 100 gal. per min., against 80 ft. head, with the supply flowing to the pump under a head of 5 ft., or to deliver 100 gal. per min., against 125 ft. head, with the supply flowing to the pump under a head of 50 ft. This characteristic is taken advantage of in designing pumps for heads higher than can be satisfactorily met by single-stage pumps, by using two or more pumps in series. These may be entirely separate and distinct pumps, the discharge of one connected into the suction of the other by pipe, or all of the pumps or stages may be housed in one casing. For ordinary motor speeds, centrifugal pumps are usually built single-stage for heads up to 100–150 ft., depending on the capacity of the pump and, therefore, the size of the impeller. As the peripheral speed of the impeller increases, either on account of larger diameter or of higher rotative speed, the allowable head per stage increases correspondingly. When several centrifugal pumps are installed in the same station, they may be so connected that by the operation of a few valves, the pumps can be operated in series against a head aggregating the combined working heads of all the pumps, the capacity remaining the same as for one pump; or they may be operated in parallel, giving the total combined capacity, the limiting head in this case being the same as for a single pump.

170. The up-keep expense of centrifugal pumps is usually small for the reason that the only moving parts in contact are the shaft and bearings. The clearance between the impeller and casing is almost always greater than the permissible wear of the bearings, so that there is little likelihood of the two coming into contact. Even if they did, this would probably be detected and the pump shut down before any damage was done.

High-head conditions require high impeller velocity, which gives high velocity to the water leaving the impeller. In order to obtain good efficiency these conditions demand high velocities in the diffusion chamber (if there be one) and in the volute. High velocity of water results in rapid corrosion of cast iron, the usual material used for volute pumps. This corrosion occurs wherever the water at high velocity comes in contact with the iron, and particularly so wherever a sudden change in direction of flow occurs which will cause shock and the formation of eddies. However, it is often found that the efficiency of centrifugal pumps increases slightly after they have been in service for a time and this is due to the scouring action of the water on the surface of the water chambers.

171. Piping connections. From the principle of operation of centrifugal pumps and especially of turbine pumps, the velocity in the pump casing is very likely to be higher than good practice would permit for velocity of water in pipes, consequently the size of the pipe connection should be calculated on the basis of allowable velocity in the pipe rather than simply to make the connection of the size of the suction and discharge openings of the pump. To avoid shock, due to sudden change of section of the pipe, this change in size of pipe should be made by means of a standard "increaser" or "reducer," and this fitting should be installed at the pump opening. As already pointed out, the suction connections must be absolutely air tight if

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satisfactory operation is to be obtained. Incidentally, also, the packing glands must be drawn up tight, but only tight enough to prevent leakage, care being taken to avoid excessive friction on the shaft at this point. Some pumps have a connection from the discharge chamber to the glands in order to keep them under a "**water seal**" at all times. When this connection is provided, the glands should be loose enough to permit constantly a slight leakage.

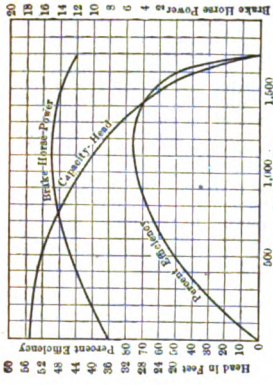


FIG. 26.—Characteristic curves of a typical volute pump at constant speed.

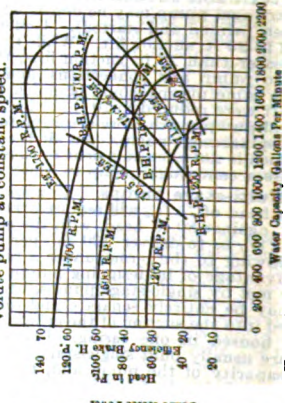


FIG. 28.—Head-delivery and power characteristics of a centrifugal pump at different speeds with curves connecting points of constant efficiency.

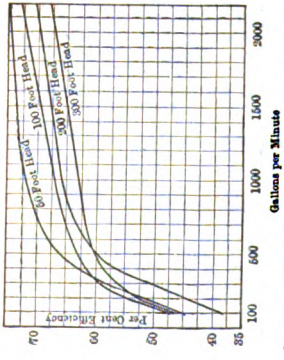


FIG. 25.—Efficiencies of centrifugal pumps designed for various head and capacities.

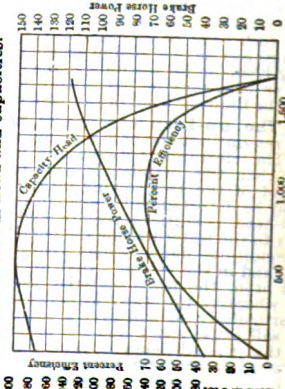


FIG. 27.—Characteristic curves of typical turbine pumps at constant speed.

172. **Characteristics of centrifugal pumps.** Fig. 25 shows typical curves of efficiency of standard centrifugal pumps designed for various heads and capacities. These curves may be compared with the curves of Fig. 23 of reciprocating pumps. Figs. 26 and 27 show the characteristic curves of typical centrifugal pumps. Attention is called to the slope of the so-called "capacity-head" curve in the two cases. In Fig. 26, the highest head is the "shut-off pressure" and the curve falls from this point on. In Fig. 27,

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the pressure rises at first above the "shut-off pressure" and then falls as the capacity is increased. While the shape of the curve depends primarily on the shape of the impeller vanes, it will be found in general, although by no means in every case, that volute pumps will show a curve similar to Fig. 26 and turbine pumps a curve similar to Fig. 27. With a capacity-head characteristic curve similar to that in Fig. 26, the horse-power curve usually reaches a maximum slightly above normal capacity and then drops off. This feature is very important in the selection of a pump for service where the head is likely to be materially reduced at times, as it will prevent the motor from being overloaded. A pump with the characteristics shown in Fig. 27 should be used only where there is no likelihood of its being operated at heads greater than, equal to, or approaching the "shut-off pressure," or where the head is likely to be reduced to a value considerably below the normal working head. At heads equal to, or greater than the "shut-off pressure," there are two capacities corresponding to each condition of head. At these points, the operation becomes unstable with a probability that the pump will discharge intermittently, the water surging up and down in the discharge pipe. With heads below normal, the capacity and the horse power keep increasing with the result that the motor is likely to become dangerously overloaded. In general, the characteristic curve of the volute pump, and at least within the "working limits," the curve of the turbine pump, show that for constant speed, the capacity increases as the head decreases and *vice versa*, with but little change of power required.

173. Performance under variable speed. Fig. 28 shows the effect of operating a given pump at variable speed. It will be noted that the efficiency, the head and the capacity all fall off rapidly as the speed is decreased, so that there is little or nothing to be gained by the use of a variable speed motor except, perhaps, in special cases. These curves also show that the power required at starting is very low, permitting the pump to be started even against normal head without the use of a by-pass and without requiring heavy starting currents in the motor—a most desirable feature.

AIR COMPRESSORS

BY JOSEPH H. BROWN

Manager, Sullivan Machinery Co.

174. Rating. The rating of air compressors is made on the basis of the piston displacement of free air per min., and in designing a motor drive, the first problem which arises is the determination of the power output required of the motor for the compressor operating under the desired conditions.

175. Measurement of discharge. The relation between the piston displacement and the amount of air actually delivered has been taken, in the past, from indicator cards, but this method is extremely inaccurate, since slippage due to leakage past the piston rings and leakage back into the cylinder through discharge valves, cannot be detected. As a matter of fact, these leakages tend to make an apparently better card and to increase the apparent volumetric efficiency. Recent tests have been made by discharging the compressed air through orifices and calculating the quantity of free air delivered per min. by the following formula (Par. 176).

176. The discharge formula may be stated as follows:

$Q = 3.64Kd^2\sqrt{HT/Pm}$ where Q = cu. ft. of air per min. at observed temperature of *upstream side* of nozzle; d = diameter of smallest part of nozzle throat in inches; H = observed water column in inches; T = absolute temperature of air entering nozzle, which is observed temperature $F + 460$; Pm = absolute mean pressure between entering and leaving sides of nozzle, lb. per sq. in.; K = coefficient of nozzle. With well-rounded edges the coefficient is between 0.98 and 0.99. The nozzle should be of such a size that the pressure on the upstream side will not be more than a pound per square inch above the atmosphere. The air delivered by the compressor is first passed into the regular discharge line receiver where the pressure is maintained constantly at the rated point by bleeding the air through a valve into a second receiver which is provided with the nozzle. The diameter of this second receiver must be at least two and a half times the smallest diameter of nozzle throat (preferably larger) and should be from 10 to 15 or more feet long.

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The quantity Q is reduced to Q_1, its equivalent at the *temperature of the compressor intake*, by the following formula $Q_1 = Q \times T_1/T$, where T_1 = absolute temperature of air at compressor intake. *The delivery of cu. ft. of air per minute* then equals Q_1.

177. Efficiency. In practice it is found that two-stage compressors show volumetric efficiencies varying from 84 per cent. to 76 per cent at speeds of about 200 rev. per min. with a terminal pressure of 100 lb. gage. Single-stage compressors under the same conditions show volumetric efficiencies varying from 71 per cent. to 57 per cent.

The above figures may be used in determining the actual amount of air delivered by the compressor. The power required per cu. ft. of air depends upon the type of compressor, whether single-stage or multi-stage, and upon the method of driving, whether direct-connected, belted or geared (Par. **180** and **181**).

178. Two-stage compression should be used for capacities over 200 or 300 cu. ft. per min., where the pressure is between 40 and 200 lb. per sq. in. Not only is there a saving in power of approximately 10 to 20 per cent., but the reduced terminal temperature permits better lubrication.

179. Theoretical power required to compress air. For the ordinary working pressure of 100 lb., the theoretical power required for isothermal compression of 1 cu. ft. of free air per min. is 0.131 h.p. To this must be added the power lost in friction and that given off as heat, during compression (Par. **182**).

180. Test of a direct-connected compressor. In a test made in New York City in January, 1912, the power input to the motor was 23.26 h.p. per 100 cu. ft. of free air per min. compressed to 100 lb. per sq. in. gage pressure and actually delivered through orifices. The compressor tested was direct-connected to a 400-h.p., 188-rev. per min., self-starting synchronous motor with belted exciter. The low-pressure cylinder was 26 in. in diameter, the high-pressure cylinder 15.5 in. in diameter, stroke 18 in., and the displacement capacity 2,070 cu. ft. at 188 rev. per min. The volumetric efficiency at this speed as shown by the orifice test was 88 per cent. The horse-power input at full-load was 425, and the indicated horse power of the air cylinders was 350. The overall mechanical efficiency including motor, exciter and compressor was 82.3 per cent.

181. Comparison of direct-connected compressor with belted compressor. For the purpose of comparison with a belted compressor where the power is usually specified as that delivered at the compressor pulley, the efficiency shown in Par. **180** may be divided into 91.5 per cent. for motor and exciter and 90 per cent. for the compressor. This gives a motor output of 389 h.p., or 21.4 h.p. per 100 cu. ft. of air delivered. Compared with isothermal compression, the overall efficiency, exclusive of motor and exciter, is 61 per cent., and with motor and exciter included, the overall efficiency is 56 per cent. In a belt drive there will be a further loss of from 5 per cent. to 10 per cent., depending upon the efficiency of the belt drive.

182. Computation of required horse power. The figures in Par. **181** may be used in computing required horse powers from tables showing power used in isothermal compression at other pressures, and will be found approximately correct for machines of over 100 h.p. rating. In the case of machines of less than 100 h.p. rating, allowance should be made for reduced mechanical efficiency of both compressor and motor. In comparing these figures with those obtained from other sources, it should be noted that these results are calculated from actual delivery, and not from piston displacement.

183. Advantages of direct connection. The ideal motor-drive for air compressors is direct connection, and this should be used wherever possible on machines of 100 h.p. and above. No power is wasted in the belt transmission, the upkeep cost of the belt is eliminated and there is a great saving in floor space. Compressors are now designed to give good volumetric efficiency at speeds up to 225 or 250 rev. per min. by the use of plate valves, unobstructed air passages, and ample discharge valve area. Self-starting synchronous motors can be obtained which will operate at the desired speed, and this type of motor is admirably adapted for such service. The exciter is usually belt-driven from a pulley on the compressor shaft.

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184. Use of fly-wheels with synchronous motor drive. Unless the compressor is of a type that requires no fly-wheel effect (such as the angle compound design) a fly-wheel must be provided, since the rotors of standard synchronous motors do not give the necessary WR^2.

185. Belt-drive is used on small compressors, also in the case of larger installations of a temporary nature, where economy of power and floor space is not imperative, or where first cost and delivery must be considered. In this connection, however, it is important to note that on the New York City tunnel of the Catskill Aqueduct, where the compressors were in service only from 2 to 3 years, the great majority were of the direct-connected type.

186. The short belt-drive has come into active use and makes a very desirable arrangement for small installations. The motor and compressor shafts are brought closely together and, by use of an idler pulley which rides on the belt, sufficient arc of belt contact is secured on both driving and driven pulleys, and the results are entirely satisfactory. For this purpose the belt should be made endless, in order that no lacing will be required. The economy of floor space obtained by this arrangement has practically done away with **gear-drive** for air compressors except in the case of very small machines of the portable type. The only redeeming quality of the gear-drive was its compactness, and it was always objectionable on account of noise and wear even when the drive was of the most improved type.

187. Regulation of air discharge. Since the demand for air is almost always intermittent, and the compressor must operate at constant speed, some method of regulating the amount of air compressed and delivered must be employed. Various devices are used. With some types of mechanically operated inlet valves provision is made to hold them open during the whole or part of the compression stroke, but any mechanism of this nature has the objection of complicated moving parts, and furthermore the compressor must be limited to comparatively slow speed to allow for proper operation.

188. Regulation by clearance control. In this method clearance spaces are provided which communicate with the cylinder through valves controlled by the governor. The compressed air, instead of being delivered to the line, passes into this clearance space and on the return stroke of the piston, returns to the cylinder and expands again behind the piston. A part of the work of compression is recovered in this re-expansion, but this method of control is inefficient because a considerable amount of power is wasted in heat which cannot be regained, and there is also some leakage.

189. Regulation by use of an unloading valve. The most satisfactory and economical method of regulation is the combination of an unloading valve on the intake cylinder and an **atmospheric relief valve** on the discharge, or high-pressure cylinder. The unloading valve on the intake is connected to the air receiver, and a rise in pressure causes it to close. All air is then cut off, and as soon as the system is pumped out, the low-pressure piston operates in a vacuum. But there will be a slight leakage past the valve and around the piston-rod stuffing box, and provision must be made for allowing this air to escape. If this is not done, a small amount of air will be carried over into the high-pressure cylinder and compressed over and over again, resulting in dangerously high temperatures and waste of power. An atmospheric relief valve is therefore provided which is operated automatically after the unloading valve is closed. This relief valve shuts off communication between the pressure line and the high-pressure cylinder, and at the same time opens a free exhaust from the high-pressure cylinder to the atmosphere.

When the pressure in the receiver falls slightly, the intake unloader opens, then the relief valve closes, and the work of compression is again taken up. This cycle is secured without shock, as the operation is comparatively gradual and as an appreciable space of time is taken to fully load or unload. With this method of control the machine is either operating at its most efficient point (full-load) or else no work is being done except that necessary to overcome the friction of the moving parts.

190. A load factor of 60 per cent. may be taken as an average figure for compressor operation. In the test referred to above (Par. 180), the compressor was equipped with combination unloading valves and the power

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required at 60 per cent. load factor was 3.1 kw-hr. per 1,000 cu. ft. of free air actually delivered at 100 lb. pressure. A compressor of the same capacity and type, but fitted with clearance control, was also tested at the same time, and at 60 per cent. load factor the power required was 3.5 kw-hr. per 1,000 cu. ft., or 12.9 per cent. greater.

191. **Starting.** No special difficulties are encountered in starting, since the compressor is started without load and the load is not thrown on until the machine is up to normal speed.

192. **Automatic starting and stopping** is not recommended for large units or for installations where the starting and stopping is at all frequent. It is of value where the compressor is of small size and the demand for air very intermittent with long intervals where no air whatever is required. The compressor should be arranged so as to start unloaded and not throw on the load until the motor is up to speed.

FANS AND BLOWERS

BY MERTON S. LEONARD

Chief Engineer, B. F. Sturtevant Co., Member American Society of Mechanical Engineers

193. **Definitions.** Fans will here include only **centrifugal fans** having inlet at centre and discharging at the periphery, either directly or through a casing which directs the air to the outlet; and **propeller fans** which move the air in an axial direction by propulsive force, similar to the propeller of a ship. **Blowers** will here include only **positive rotary blowers,** which, by the action of a rotating impeller or impellers in a very closely fitting casing, create pressure by direct compression.

194. **Characteristics of fans and blowers.** Fans and blowers, like pumps and unlike most other machines, may operate with equal efficiency at any speed which their mechanical strength safely allows. They may also discharge, in practice, through orifices varying in area from that of their full discharge, to a very small per cent. of the full outlet. The **efficiency** varies with different orifice areas, but not according to any fixed law for all designs.

The **horse power** for any fan or blower, if the area of the discharge orifice remains unchanged, varies directly as the cube of the speed; also, if the area of the discharge orifice remains unchanged and the speed is constant, the horse power varies directly with the density of the gas being handled.

195. **The horse power of a centrifugal fan,** if the speed remains unchanged, generally decreases as the area of discharge orifice is decreased. In some designs the horse power with rated orifice is not over one-third of the horse power with orifice equal to area of fan outlet, and in other designs it is very little less at rated orifice than with unrestricted orifice.

196. **The horse power of a propeller fan,** if the speed remains unchanged, increases as the area of the discharge orifice is decreased. In some designs the horse power with rated orifice is not over one-quarter of the horse power with complete restriction.

197. **The horse power of a positive blower,** if the speed remains unchanged, increases as the area of the discharge orifice is decreased. Owing to the small clearances in these machines the horse power increases greatly with decrease of orifice, but blowers are provided with relief valves which can be set to limit this as desired.

198. **Types of motors adapted to various fans.** For driving centrifugal fans, with direct-current supply, shunt-wound motors should be used. For driving propeller fans either shunt-wound or series-wound motors can be used, with direct-current. The series-wound motor is preferable, if readily obtainable. For driving positive blowers, with direct-current supply, shunt-wound motors should be used. Induction motors are commonly used, with alternating-current supply, for all types.

199. **Starting torque.** As the torque required to start any fan or blower is only that required to overcome the friction of the bearings, which are usually two in number, and the inertia of a comparatively light rotating part, no special consideration need be paid to this feature.

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200. Method of control (direct-current). When a fan or blower is required to operate at only one speed under all conditions of service, a starting rheostat with no-voltage release should be used. If there is a possibility of a condition arising in the system which will increase the horse power above the capacity of the motor, as in the case of a centrifugal fan so arranged that all air resistance may be removed by the changing of dampers or opening of doors, or in the case of a propeller fan which may have its delivery entirely blocked by a shutter, or in the case of a positive blower which may have its delivery restricted by the closing of blast gates, an overload release should also be provided.

A starting and regulating rheostat with no-voltage release should be used where a fan or blower is required to operate under varying conditions at speeds below normal, but operates the greater part of the time at normal speed. Such equipment should also be used where speed varying below normal is required, and the cost of energy is not important. See Par. 519.

When a fan or blower is required to operate at varying speeds, and operates the greater part of the time at less than its maximum speed, or where varying speed is required and economy of operation is more desired than low first cost, a starting rheostat with no-voltage release should be used in combination with a field controller. The speed, with this arrangement, is adjusted by variation of resistance in the field circuit. From 10 per cent. to 25 per cent. speed increase by field control and 50 per cent. decrease by armature regulation, are very common specifications for fan motors in high-grade installations.

201. Remote control. Any of these devices (Par. 200) may be arranged for remote control, or for automatic speed control to maintain constant volume or constant pressure of air from the fan or blower, or to maintain constant steam pressure at the boilers in the case of mechanical draft fans. Automatic speed control of fan and blower motors is not recommended, since it is very likely to give trouble on account of its complexity and refinement.

202. Method of control (alternating-current). Any method of control which is adaptable to alternating-current motors in general is suitable for alternating-current fan motors. However, such motors are usually arranged to operate at only one speed, and are provided only with a starting device. If it is necessary to vary the volume or pressure of the fan or blower, it may be accomplished by throttling the air with a damper.

203. Methods of direct connection. Whenever feasible it is best to mount the fan wheel directly upon the motor shaft. This can usually be done with small centrifugal fans and with propeller fans up to about 60 in. diameter; however, the deflection and the critical speed of the shaft should be investigated to determine whether or not this is safe.

When it is not feasible to mount the fan wheel upon the motor shaft, it is best to provide the fan with two bearings and connect the motor by means of a flexible coupling. It is more common, however, on account of low cost and space economy to provide the fan with one bearing and connect the motor by means of a solid-flange coupling. If this is done, care must be taken properly to align the bearings, and to maintain the alignment.

204. If a fan handles hot gases, means must be provided for the protection of the motor from the heat. This is accomplished by cooling the shaft or the bearings with water, or by separating the motor and the fan with a long shaft extension, or by driving the fan with a belt or chain.

205. Suppression of noise. If there is danger of noise being transmitted through the air ducts, as in auditoriums, theatres, schools, churches and hospitals, it is often better to drive the fan by belt from the motor. This is particularly true of alternating-current motors.

206. Belt drive for fans. It is often possible to use a smaller and less costly motor by use of belt-drive, when the fan speed is lower than necessary for a motor of the same horse power. It is generally preferable to belt alternating-current motors, because the most desirable speed of a standard fan for a given duty is seldom the same as the available motor speed, making it necessary to build a special fan, and thus increasing the cost, if direct-connected.

It is desirable to drive by belt, when the required fan speed or the fan horse power is in doubt, as an inexpensive change in size of pulley will correct the error, if one is made.

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207. Method of motor application to blowers. Blowers are essentially slow-speed machines. It is, therefore, almost always desirable to belt or gear the motor. If geared, the motor and the blower should be mounted on the same base to assist in maintaining alignment.

208. Approximate horse power of centrifugal fans. The horse power required to drive any centrifugal fan may be represented by the following formula:

$$\text{h.p.} = K\left(\frac{T}{1000}\right)^3 DW\left(\frac{w}{0.075}\right) \quad (5)$$

Where K (Par. **210**) is a constant depending upon the design and upon other conditions, T is the peripheral velocity or the tip speed of the blast wheel in ft. per min.; D is the mean diameter of the blast wheel in feet; W is the mean width of the blast wheel in feet; w is the absolute density of the gas handled, in lb. per cu. ft.; 0.075 is the weight of standard air at 65 deg. fahr. in lb. per cu. ft.

209. Approximate horse power of propeller fans. The horse power required to drive any propeller fan may be represented by an expression of the form,

$$\text{h.p.} = K_1\left(\frac{T}{1000}\right)^3 A\left(\frac{w}{0.075}\right) \quad (6)$$

Where K_1 (Par. **211**) is a constant depending upon the design and upon other conditions, T is the peripheral velocity or the tip speed of the wheel in ft. per min.; A is the gross area of the wheel in sq. ft.; w is the absolute density of the gas handled in lb. per cu. ft.; 0.075 is the weight of standard air at 65 deg. fahr. in lb. per cu. ft.

210. Table of constants for centrifugal fans
(B. F. Sturtevant Company)

Type of fan	Values of K		
	Minimum	Normal	Maximum
Paddle-wheel with 6 to 10 straight blades and $W = 0.45D$	0.0020	0.0060	0.0090
Steel pressure with 24 backward curved blades and $W = 0.15D$	0.0020	0.0050	0.0142
Slow speed conveying with 18 forward curved blades and $W = 0.25D$	0.0026	0.0100	0.0260
Single-inlet multiblade-drum with 60 narrow curved blades, inclined forward and $W = 0.50D$	0.0065	0.0240	0.0390
Double-inlet multiblade-drum with 60 narrow curved blades, inclined forward and $W = 0.50D$	0.0091	0.0330	0.0550
Double-inlet multiblade-drum with 60 narrow curved blades, inclined forward and $W = 1.00D$	0.0065	0.0250	0.0390
High speed with 16 backward inclined blades and $W = 0.8D$	0.0008	0.0017	0.0019

211. Table of constants for propeller fans
(B. F. Sturtevant Company)

Type of fan	Values of K		
	Minimum	Normal	Maximum
Sturtevant propeller	0.0004	0.0006	0.0020
Multiblade disc	0.0009	0.0012	0.0016
Blackman propeller	0.0007	0.0012	0.0033
Davidson propeller	0.0009	0.0015	0.0028

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212. Horse power of positive blowers. The horse power of a positive blower at any speed varies over such a wide range, depending upon the pressure, that any rule for the approximate horse power would have to take into account the volume and the pressure of the air and the displacement of the blower, all of which are so difficult of determination that it is thought best not to attempt to state a rule here. For estimating purposes, the efficiency of such machines may be taken as 60 per cent.

COAL AND ORE HANDLING MACHINERY

BY C. D. GILPIN

Electrical Engineer

213. Definition. The term "coal and ore handling machinery" is intended to cover the apparatus used in re-handling coal and iron ore between the mine and point of ultimate consumption. Such apparatus consists in

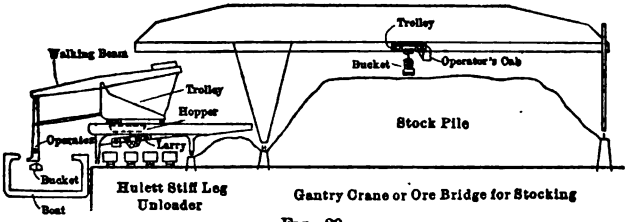


FIG. 29.

the main of unloaders, bucket-handling gantry cranes, car dumpers, self-propelled transfer cars and belt conveyors. Fig. 29 represents a stiff-leg unloader, with a gantry crane for stocking such ore as is not to be immediately loaded into cars. Fig. 30 shows a gravity-type unloader and a gantry crane.

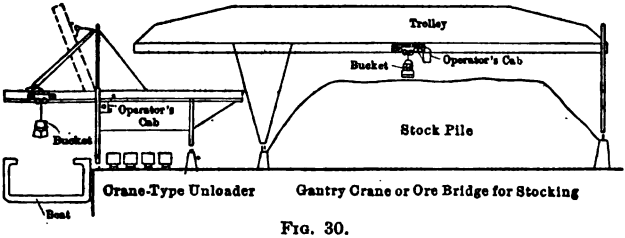


FIG. 30.

214. Motors for severe service are usually of the mill type with large shafts, fire-proof insulation, heavy frames, small moment of inertia of armature and great commutating capacity. Shafts are generally tapered at the pinion end to allow for easy removal of the pinion, and axle bearings are often used where a gear ratio of about five-to-one is desired. The frames are generally entirely enclosed, although many of the larger sizes are constructed with part of the upper frame cut away in order to facilitate the dissipation of heat. It is possible that in the future, forced ventilation may become common practice, as is already the case in electric locomotives.

215. Motors for light service where direct current is available, and of 25 h.p. or under, are usually of the crane type. This construction is much cheaper than the mill-type construction, yet is quite satisfactory for intermittent service where no severe overloads occur. The frames are entirely enclosed, as heating is not a consideration.

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216. Motors for car dumpers, where there is usually abundant space available, and where the electrical apparatus is well protected from the weather, are often of the open type with commutating poles. The speed of rotation is preferably lower than for the mill motor, owing to the greater radius of gyration of the armature.

217. Motors for transfer cars are commonly either of the railway or mine type, the latter often being preferable on account of their low speed, high torque and large gear reduction. Standard drum-type controllers are ordinarily furnished with these motors.

218. Mill motors, where alternating current only is available, may be obtained for 3-phase, 25-cycle, 220-volt or 440-volt circuits. For a frequency of 60 cycles it is necessary to use an open type of frame, an outboard bearing being desirable for sizes above 25 h.p. Alternating-current motors should be of the slip-ring type, except for belt conveyors with light starting requirements, where squirrel-cage motors may be used. They should be of sturdy mechanical construction, and should be wound for high torque. Low rotor speeds are desirable as tending to keep the acceleration load at a minimum.

219. Controllers for heavy duty are always of the contactor or magnetic-switch type with overload and automatic acceleration relays. Dynamic braking for lowering buckets, etc., is practically universal; not only is the energy of the lowered mass dissipated in resistors instead of brake friction, but the operator is given a very delicate control by means of his master controller instead of having to manipulate an air or hand brake. Where direct current is not available, dynamic braking is obtained by means of a small low-voltage generator set, which provides direct current for exciting the stator winding of the motor lowering the load, thus allowing it to become an alternating-current generator. Since only part of the winding can be used for this purpose, and since an induction motor possesses inherently a limited torque, this system of dynamic braking is not as reliable as where direct-current motors are used. See article on "Motor Control" elsewhere in this section.

220. Distribution systems. The standard source of energy, especially on the lower lake docks (Lake Michigan and Lake Erie) and in the great steel plants, is a 250-volt direct-current circuit, a metallic return circuit being generally used. In purchasing energy, part of the charge is usually based on the peak loads, and where these peaks are figured on the basis of five seconds or less, the cost of energy can often be substantially reduced by the introduction of a fly-wheel balancer set in connection with rotary converters.

221. A fly-wheel balancer set consists of a direct-current machine of very high commutating capacity mounted on the same shaft with a fly-wheel and so arranged that when the station load exceeds a certain amount, the field of the balancer machine will be automatically strengthened so that energy will be given out by the fly-wheel as it decreases in speed. When the demand ceases, the balancer field is weakened and the machine becomes a motor, thus accelerating the wheel to normal speed. Such balancers are commonly rated at from 200 kw. to 300 kw. of continuous capacity, with a commutating capacity for 200 per cent. overload; the fly-wheels vary from 25,000 lb. (11,350 kg.) to 50,000 lb. (22,700 kg.) with rim speeds of about 16,000 ft. per min. (4,880 m. per min.) for cast steel wheels and 28,000 ft. per min. (8,540 m. per min.) for laminated plate wheels. A very careful study of load conditions and the power contract is desirable before installing one of these balancer sets.

222. The power requirements of coal and ore handling apparatus may be considered under two classes: (a) those in which a fixed force or constant torque predominates, such as gravity or friction, and (b) those in which acceleration or variable torque is the main feature. To the first class belong the hoist motions, where the speed is comparatively low and the requirement for acceleration is a small part of the total power. For this type of motion a compound-wound motor has been commonly used, the compound winding being originally provided to facilitate dynamic braking. Later developments of control have made dynamic braking practicable for series motors, and the tendency now is toward the use of that type of winding. The control should include at least one "power point" in the lowering direction.

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and should be so arranged as to provide dynamic braking or armature shunting at all times while lowering, so that it will be impossible for the load to overhaul the mechanism at a dangerous speed. An emergency spring-closing switch is often desirable; this should be so arranged as to connect the armature in series with the field and a small amount of resistance, in case of failure of the line current. The motors should be provided with magnetic brakes, the shunt type of winding being preferable in many cases.

223. The approximate motor loads may be obtained as follows: The hoisting h.p. equals the hoisted load in lb. multiplied by the hoisting speed in ft. per min., divided by 33,000 and again divided by the efficiency expressed as a decimal. The nominal lowering h.p. equals the lowered load in lb. multiplied by the hoisting speed in ft. per min., divided by 33,000 and multiplied by the efficiency. In this case the lowering h.p. really represents current or torque as read on the characteristic curve of the motor. Variations in lowering speed are obtained by changing the dynamic braking resistance and thereby the motor voltage for the same current value. The approximate heating of the motor can be determined as shown in Par. 221.

224. The power required by a belt conveyor is, normally, almost constant. The size of motor is commonly obtained by referring to the manufacturer of the conveyor. The motor should have a continuous rating and may be of the variable speed type. **Electrical weighing devices** are sometimes used to weigh the material as it passes a given point. Such a device consists essentially of a magneto generator driven by the conveyor, connected in series with a resistance which varies inversely with the instantaneous weight of the material at that point on the conveyor. It is obvious that the output of the generator depends both on the speed of the conveyor and on the amount of material which it carries; an indicating wattmeter will therefore show the rate at which the material is being handled, and a watt-hour meter will record the total amount of material handled during a given time.

225. Equipment for transfer cars and trolleys. In the case of transfer cars and the trolleys of unloaders and bridges, acceleration is the predominant factor. For loads of this kind, two motors are used as a rule, in order to obtain good traction; in such cases, series-parallel control is generally preferable. If the motors are permanently connected in parallel, it is safer to provide a separate set of reversing contacts for each armature. Armature-shunting points are occasionally employed to obtain very low speeds, and dynamic braking is sometimes provided in the case of a gantry crane or unloader trolley. To obtain dynamic braking for a series-wound trolley motor, it is necessary to connect the field in series with a resistance across the line, so that the characteristics of a shunt generator may be obtained. An air brake is generally preferable for trolley service, except when the operator is located at some distance from the mechanism, in which case the motor should be provided with a magnetic brake, preferably of the disc type, and the controller should give dynamic braking on or near its central position.

226. The frictional resistance of the ordinary trolley may be taken at 25 lb. per ton; for a transfer car with standard trucks, 15 lb. per ton is ample. The horse power for the final assumed speed should first be figured as follows: h.p. = friction force at rim of wheel multiplied by the speed in ft. per min. and divided by the efficiency (expressed as a decimal) and by 33,000. About twice the result should be taken as the nominal horse power required, this value being based on a rise of 75 deg. cent. in 1 hr. The performance of the trolley or car can then be easily worked out by means of the motor curves, the step-by-step method being used as explained in Par. 233. It will sometimes be found that the motor chosen is too small; where there is any doubt, the moment of inertia of the armature should be obtained and should be translated into its equivalent weight at the trolley speed. The calculations should then be gone over more carefully; for slow trolley speeds, the inertia of the armature becomes a very considerable part of the whole.

227. The longitudinal drive of an unloader or bucket-handling gantry partakes of the nature of a trolley drive, but owing to the much lower speed and higher friction, inertia plays a smaller part, and dynamic braking is unnecessary. Friction may be taken at about 40 lb. per ton, although this figure is quite uncertain. The heating is not a factor in this class of

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service, but sufficient commutating capacity should be allowed to take care of a wind-pressure equivalent to one and one-half times the friction; this is merely a general rule, but is one which works well in practice. In some cases long gantry cranes are driven by independent motors at each end; this scheme is quite successful, even with series motors, although an automatic device should be provided to prevent one end from leading the other. With this type of drive, the motors should be provided with magnetic brakes; the disc type being preferable because the shock when stopping is less than with the post brake. For the ordinary gantry or unloader, one motor is generally connected by bevel gears to both trucks; a mechanical foot brake which is held in the released position by the weight of the operator is preferable to a magnetic brake in this case, since it can be applied more gently.

228. The gear efficiency of one reduction of cut spur gears in this class of work may be generally taken as 95 per cent.; for cut bevel gears, 90 per cent. For important motions, the cut herringbone gear is becoming popular; it should have an efficiency of at least 97 per cent. if properly erected. The **coefficient of friction** for the ordinary bearing will average about 0.0[illegible] while for sheaves it is better to allow a value of 0.07. These figures may be safely followed except in special cases, such as in gearing for longitudinal drives where there is decided likelihood of poor alignment of shafts and gears.

229. The calculation of power house or substation capacity for a dock is a long and tedious process, since it is a matter of some conjecture as to just how the peak loads, which are usually violent, will coincide. A 10-ton stiff-leg ore-unloader having a total capacity of 400 h.p. in five motors will show a momentary peak load of 1,200 amp. and an average load of 400 amp. Two such machines working together will occasionally take 1,800 amp. for 1 or 2 sec. One 15-ton stiff-leg ore-unloader with seven motors totalling 700 h.p. and requiring an average load of about 500 amp. will draw a peak of 1,800 amp. The maximum current for four such machines, however, will not exceed 4,000 amp. Gravity-type unloaders are likely to show a higher proportional peak load because practically all the work is done by the hoist and the trolley; operators of this type of machine are generally cautioned not to work too nearly in synchronism with the other unloaders if the power house capacity is limited. If possible, it is much better to obtain data from an installation similar to the one contemplated. In any case the generators or converters should have a high commutating capacity and all circuit-breakers should have time-limit relays. The tendency of late is distinctly toward the purchase of energy where possible; in many cases an excellent rate can be obtained owing to the fact that work is carried on by night as well as by day. A better rate is sometimes obtainable by reducing the demand during hours of normal central-station peak load.

230. Example of calculations for typical ore-handling gantry crane. The hoist-motion calculations are given in Par. **231**, the trolley calculations in Par. **232**, and the bridge calculations in Par. **233**. The following calculations relate to the case of a typical 15-ton ore-handling gantry crane. The estimated average duty is to lift one bucket of ore 30 ft. every min., the average distance to be trolleyed being 200 ft. Assuming that 10 per cent. of the total time is lost in moving the crane longitudinally, etc., the speed must be such as to perform the given cycle in 54 sec. Estimate the time in which the trolley will not be working, as follows: Closing bucket, 6 sec.; hoisting clear of ore pile, 2 sec.; opening bucket, 4 sec.; lowering bucket after trolley comes to a standstill, 2 sec.; total, 14 sec. Time available for trolley trip in one direction, 20 sec. Average speed of trolley, 600 ft. per min. Assume a maximum trolley speed of 900 ft. per min. and a hoisting speed of 180 ft. per min.; the latter speed is not required for the assumed cycle, but will be useful when making long hoists with a short trolley travel.

231. Calculations for hoist motion (Par. 230). The hoist motion is assumed to be of the type in which each of two motors is geared through two reductions to its own drum, each of the two drums carrying one of the two sets of cables necessary for operating a clam-shell bucket. No. 1 motor closes the bucket; Nos. 1 and 2 hoist the bucket together; No. 1 opens the bucket; and No. 2 lowers it, No. 1 running down with practically no-load. The efficiency may be assumed roughly as 90 per cent. The ore will weigh 33,600 lb.; assume the bucket weighs 30,000 lb., making a total of 63,600 lb. The hoisting horse power per motor $= (63{,}600 \times 180)/(33{,}000 \times 0.90 \times$

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193; or say 200 h.p. The lowering horse power for No. 2 motor $(30{,}000\times180/33{,}000)\times0.90=147$ h.p.; or say 150 h.p. Assume the erage closing load for No. 1 motor is 150 h.p., and for opening, 50 h.p. he root-mean-square or effective horse power for No. 1 motor will then be $150^2\times6+200^2\times10+50^2\times4)/60]^{\frac{1}{2}}=95$ h.p. The mean effective horse ower for No. 2 motor $=[(200^2\times10+150^2\times7)/60]^{\frac{1}{2}}=96$ h.p., assuming iat actual lowering takes place in 7 sec.

The smallest motor which suggests itself for this service is one having an itirely enclosed frame and a mill rating of 150 h.p.; the mill rating is based a the power the motor can develop for 1 hr. with a temperature rise not to ceed 75 deg. cent. Investigation of the manufacturers' data shows that ie 150-h.p. mill-rated, fully enclosed motor will not have sufficient heat- g capacity if the crane is to be operated at full speed continuously, although ie commutating capacity is ample. This same motor, however, if built ith a semi-enclosed frame will have a mill rating of approximately 165 h.p. id a root-mean-square rating of about 130 h.p., which is ample for the rvice. Generally speaking, there is less trouble from heating than is indi- ated by the calculations, owing to unavoidable interruptions to continu- us operation, and to good ventilation due to the movement of the trolley.

232. Calculations for trolley motion (Par. 230). Assume that the olley with bucket and ore weighs 170,000 lb., and is driven by two motors, ich geared through two reductions to one of the four axles. Take the ictional resistance per motor at $25/2{,}000\times170{,}000\times\frac{1}{4}=1{,}060$ lb. Final .p. $=(1{,}060\times900)/(33{,}000\times0.90)=32$. Assume two 80-h.p. [temperature se of 75 deg. Cent. for 1 hr.] series-wound motors; from the characteris- c curve it will be found that at 32 h.p. the motor speed equals 820 rev. per in. and the torque equals 205 lb. at 1 ft. radius. Therefore the gear ratio ust be such that the desired trolley speed of 900 ft. per min. is equivalent to motor speed of 820 rev. per min.; then ft. per min. $=(900/820)\times$ rev. per in. $=1.1\times$ rev. per min.; also the force at the rim of the wheel will have he same ratio to the motor torque as the friction force has to the friction orque; or, force $=(1{,}060/205)\times$ torque $=5.17\times$ torque. Assume effect of rmature weight equal to 1,500 lb. at 0.7 ft. radius; equivalent weight of ne armature at trolley speed $=[1{,}500\times0.9\times(2\pi\times0.7\times$ rev. per min.$)^2]/$ ft. per min.$)^2=([1{,}500\times0.9\times(2\pi\times0.7\times$ rev. per min.$)^2]/(1.1\times$ rev. per in.$)^2=2{,}160$ lb.; or say 5,000 lb. including gearing. Total weight per otor for acceleration $=85{,}000+5{,}000=90{,}000$ lb. Assume that accelera- ion while short-circuiting the resistance is 2.5 ft. per sec. per sec., which s as high a value as the operator can endure with comfort; this initial rate f acceleration is determined by the rapidity with which the starting re- istance is cut out. Since the force of acceleration $=F_a=$ (wt. in lb./g) (acceleration in ft. per sec. per sec., then $F_a=(90{,}000/32.2)\times2.5=7{,}000$ lb. ince the friction force is 1,060 lb., the total force $=7{,}000+1{,}060=8{,}060$ lb. lotor torque $=T=8{,}060/5.17=1{,}560$ ft-lb. From the characteristic curve, hen $T=1{,}560$, h.p. $=119$; rev. per min. $=402$. Therefore ft. per min. $=402\times1.1=442$, and ft. per sec. $=7.4$. This is the speed which is attained t the instant the last section of resistance is cut out. The time $=t_1=$ peed/acceleration $=7.4/2.5=3.0$ sec. The distance $=d_1=$ average speed $\times$ time $=(1/2)\times7.4\times3.0=11$ ft. Afte‡ the starting resistance is cut out, he trolley will continue to accelerate at a diminishing rate, as long as the orce supplied by the motors exceeds the friction force. Assume that the orse power has decreased to 60; then from the motor curve, rev. per min. $=560$. Since ft. per min. $=1.1\times$ rev. per min., the ft. per min. $=616$, or ft. per sec. $=10.3$, and the increase $=2.9$ ft. per sec. The average speed $=(10.3+7.4)/2=8.85$ ft. per sec. Referring again to the curve, $T=560$, herefore $F=2{,}900$ lb.; $F_a=F-F_f=2{,}900-1{,}060=1{,}840$ lb., acceleration $=$ $=g\times F_a/90{,}000=0.66$, average $A=(2.5+0.66)/2=1.58$, $t_2=$ (increase in peed)/(average acceleration) $=2.9/1.58=1.8$ sec., $d_2=8.85\times1.8=16$ ft., otal time up to this point $=t=3+1.8=4.8$ sec.; total distance up to this oint $=d=11+16=27$ ft. Assume the horse power has dropped to 35; hen rev. per min. $=760$, ft. per min. $=836$, ft. per sec. $=13.9$, increase $=3.6$, verage speed $=12.1$ ft. per sec.; $T=240$, $F=1{,}240$, $F_a=180$, $A=0.06$, aver- ge $A=0.36$, $t_3=10.0$ sec., $d_3=121$ ft., $t=14.8$ sec., $d=148$ ft.. Assume trolley asts for 1 sec. at 13.9 ft. per sec.; $t_4=1$, $d_4=14$ ft., $t=15.8$ sec., $d=162$ ft. ssume retardation $=2.5$ ft. per sec. per sec.; $t_5=13.9/2.5=5.6$ sec., $d_5=39$ t., $t=21.4$ sec., $d=201$ ft. The time originally allowed for a trip one way

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was 20 sec., but since the trolley will return light at a somewhat higher speed the gear ratio originally assumed is close enough. If the heating is figured for the loaded trip and for one-half the cycle, the results will be on the safe side. Mean effective h.p. = $\sqrt{[(119^2\times3)+(119^2\times1/2\times1.8)+(60^2\times1/2\times1.8)+(60^2\times1/2\times10)+(35^2\times1/2\times10)]/[60\times\frac{1}{2}]}=52$. A fully enclosed mill motor can keep up this cycle for about 3 hr., but not indefinitely. If the crane will not operate for over 3 hr. at any one time, 80-h.p. mill-rated entirely enclosed motors should be used. For continuous operation use the same motors with the semi-enclosed frames, which will have a mill rating of about 90 h.p. and root-mean-square rating of about 70 h.p.; or if necessary, forced ventilation may be used with the totally enclosed motors. In any case, the armature, fields, etc., will be the same, the difference in rating being due to the different methods of cooling. The maximum loads to be commutated should not exceed those shown on the motor curve.

233. Calculations for bridge drive (Par. 230). Assume that the total crane weighs 1,200 tons, and that a 2-motor longitudinal travel drive is desired. Friction force per motor at 40 lb. per ton = $40\times1,200\times\frac{1}{2}=24,000$ lb. Assume that a speed of 75 ft. per min. is desired, and that each motor has one spur-gear and two bevel-gear reductions. The efficiency would be approximately 77 per cent. The friction load per motor = 71 h.p. If 80-h.p. mill-rated motors were used, the friction torque read from the curve would be about 720 lb. at 1 ft. radius. Assuming the wind load = 36,000 lb. and acceleration at 0.25 ft. per sec. per sec. = 9,300 lb., the total maximum load = 69,300 lb. and approximate maximum torque = $(69,300/24,000)\times720=2,080$ ft.-lb., which is well within the commutating limit of an 80-h.p. mill motor. Note that the wind load to be resisted by the mechanism may be greatly in excess of the above; hence rack drives are sometimes used for greater safety.

TELPHERAGE SYSTEMS

BY H. McL. HARDING

Consulting Engineer, Associate American Institute of Electric Engineers

234. Classification. There are two main divisions of telphers, automatic telphers and man-telphers. **Automatic telphers** are those which are driven

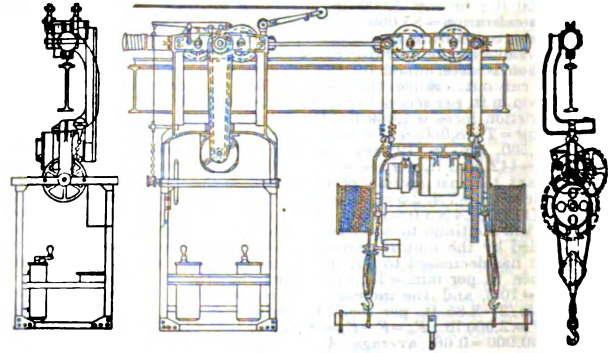


FIG. 31.—Telpher train.

by electric motors, the control being apart or remote from the telpher. The original telphers were automatic, the telpher being placed in the middle of the train. The chief use of the automatic telpher is for coal, ore and bulk material. **Non-automatic or man-telphers** are those which are controlled by an operator who travels with the load, and who operates both the telpher and the hoists from a cab or cage which is attached to the telpher

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or the carriage. It is employed for bulk material, like the automatic telpher, and is also used for the hoisting and conveying of miscellaneous material, boxes, cases and barrels, the package freight of railways and the mixed cargoes of steamships, see Fig. 31.

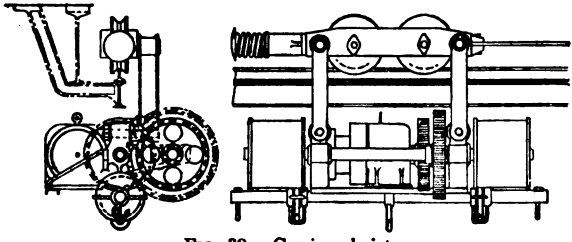


FIG. 32.—Carriage hoist.

235. Suspension. A telpher is suspended from one or more wheels in tandem, of which one or all are driven by the electric motor or motors.

236. Clearances. In the minimum-headroom 2-ton (4,000 lb.) type designed for railway and steamship terminals (Fig. 32) the vertical space from the underside of the roof girders to the bottom of the hoist-hook is 4 ft. 9 in. (144.8 cm.). The width of the hoist is 3 ft. 3 in. and 4 ft. 8 in. to the limit line for 10-deg. swing. From the centre of the rail to the inner limit of the telpher and hoist is 16 in.

237. Energy supply, in the form of either direct or alternating current is communicated to the motors by conductors which lie parallel to the track, the contact being made by shoes or wheels. Sometimes storage batteries, suspended from the telpher or the carriage, are employed. On steep grades the telpherage traction, in some installations, has been assisted by supplementary cables, either fixed or movable.

238. Motors. The sizes of motors for telphers and hoists will depend upon the class of work to be done; the motors for telpher-tractors vary from 5 to 15 h.p., and for the hoists from 3 to 75 h.p., the loads being from 500 lb. to 30,000 lb. The load factor for the tractor motor is 0.25 and for the hoisting motor 0.16. The driving wheels and the motors may be connected by gears or by chain drive. The maximum service efficiency of the motors is that corresponding to the efficiency obtained between one-half and three-quarters full-load. The motors are of slow or medium speed. Direct-current, 250-volt or 500-volt, series-wound motors are preferable for tractors and hoists although alternating-current motors afford satisfactory results. The motors should be dust and weather proof, and should have a 50 per cent. reserve in their rating. The average combined efficiency of the motors and gearing, for the tractor and hoist, is from 65 per cent. to 75 per cent.

239. Brakes. The telpher brake is of the mechanical type, and the hoist brake is of either the electro-mechanical or electro-dynamic types. Spur gears and chain drive on the tractor transmit the power from motor to track wheels, and either spur or worm gear is used to transmit power to the hoisting drum.

240. Trackage. Telphers either run in one direction on a closed track circuit (Fig. 30), or to and fro over a single line. On the single line the automatic telphers reverse themselves on completing their trips. The spacing between the cars is automatically regulated by a block system, and the cars are also automatically controlled at switches and crossings. The track consists of either a cable, or a T-rail supported on a wooden stringer, or upon the top or lower flange of an I-beam. There are also track rails of special section. The radii of the curves are from 8 ft. to 20 ft.

241. Track supports. The track is supported on brackets attached to buildings, or is supported on "A" bents. Supports under straight track are spaced 20 ft. apart, and on curves the spacing is 8 ft. For long spans cables or trusses are used.

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242. Tracks may be fixed or movable. In Fig. 33 the side tracks *B.B'*. are fixed, but *C* is movable, being attached to a travelling bridge. The speed of this bridge is from 300 ft. to 900 ft. per min. The motor driving this bridge would have a load factor of 0.16.

The telpher train passes from the side track *B* by means of a gliding switch, upon the movable track *C*. This track therefore may be placed anywhere over the area between the fixed side-tracks. The telpher returns by means of the track *B'*, to its starting-point. By the operation of this movable track, all the space can be served; this operation is called **transferage.** The minimum allowable radius of curves is 8 ft.

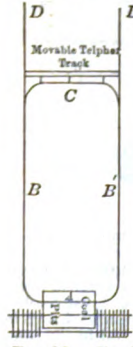


FIG. 33.—Typical arrangement of telpherage tracks.

243. Performance. The loads hoisted and conveyed on telpher hoists have been as high as fifteen tons. The maximum speed of conveying on a straight level track is about 1,000 ft. per min. The running speed is reduced at curves, according to their radii.

244. For terminal work, the capacity of each hoist is 2 tons at 60 ft. per min. (18.288 m. per min.). Two hoists can be combined so as to raise 4 tons. The motors being series-wound, the speed of hoisting will increase as the load is diminished.

245. For freight handling, from two to four carriage hoists constitute a train which has a total maximum carrying capacity of 8 tons. Such trains are used for assorting as well as for distributing, according to consignments. Many telphers can be operated in one installation, the number being limited only by the design of the track layout. In freight or cargo handling, the fixed overhead tracks may be parallel or at right angles to the surface railway tracks or to the waterfront wall, but preferably at right angles.

246. Installation costs. The overhead trackage, made part of and attached to the building structure, costs the same in proportion as other structural steel. The weight, including the brackets, averages about 50 lb. per lineal foot. The steel is fabricated at the mill.

STEEL MILLS

BY WILFRED SYKES

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247. Classification. Rolling mills are usually named after the material produced by them, although they are sometimes classified according to the layout of the mills. The principal types of mills are as follows:

(a) **Blooming mills,** rolling ingots, as cast, to blooms or billets. All material rolled in a steel mill must pass through the blooming mill or its equivalent, to be reduced to proper dimensions for handling in the finishing mills. The mills are built either two-high reversing, or three-high running continuously in one direction.

(b) **Slabbing mills** (modification of the two-high blooming mill) produce slabs with finished edges, which are afterward rolled into plates. Vertical rolls are provided for finishing the edges.

(c) **Billet mills** are usually of the continuous type, with rolls in tandem, and roll material from the blooming mill to a suitable size of billet for the finishing mills. Material passes directly from one stand to the other, the speed of the rolls being arranged to correspond to the reduction in area after each pass.

(d) **Plate mills** may be either two-high reversing, or three-high running continuously in one direction, and roll slabs to plates of various thicknesses. They are sometimes provided with vertical rolls for finishing the edges of the plates and are then known as universal mills.

(e) **Structural mills** are usually three-high and are used for rolling girders, heavy angles, channels, etc. In small plants such material may be rolled by the reversing-blooming mill.

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(f) **Merchant mills** are used for rolling small angles, channels and all types of profiles. They are usually three-high, with the finishing stand sometimes two-high.

(g) **Bar mills** are usually three-high, and generally consist of roughing stand and a separate finishing stand. These are used for rolling bars of all sections and sizes.

(h) **Rod mills** are special types of bar mills, and are used for rolling small sections at high speeds.

(i) **Rail mills** generally roll blooms or heavy billets to rails of various sections, and are made two-high or three-high, according to the layout.

(j) **Sheet mills** roll 0.5-in. to 1-in. bars to sheets of all gages; they are always two-high, and generally have separate roughing and finishing stands.

In addition to the foregoing types, there are several other forms of construction, used for rolling certain sections of material, but their use is generally confined to one particular installation.

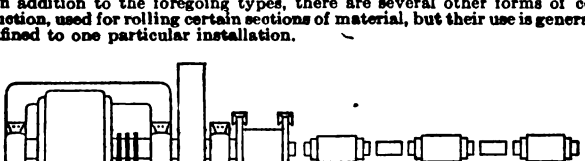


FIG. 34.—Simple mill for rolling light sections.

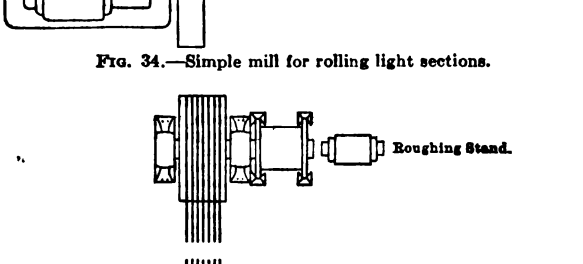


FIG. 35.—Mill with separate roughing stand.

248. Arrangement of mills. The simplest type of mill, having more than one stand, is arranged on one axis, all stands being driven by one set of pinions in the middle or at one end of the mill (Fig. 34). This type of mill is generally used for rolling small sections only, but is occasionally used for heavy sections when transfer tables are provided to move the metal from one stand to the other.

The usual arrangement for rolling light sections is shown by Fig. 35, the roughing stand runs at a slower speed than the finishing stand, and usually has larger rolls to obtain greater strength, in order that large reductions can be made. The metal is roughed down to such size that it can be readily handled by the higher-speed finishing stands. The motor is generally direct-connected to the finishing stands, the roughing stands being rope driven. A better arrangement is to drive the roughing and finishing stands separately, so that the speed of each can be adjusted for different products to give the maximum output.

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Occasionally the various stands are arranged on one axis, the finishir stands being separately driven to give the proper speed adjustment. Tl object of driving the finishing stands at different speeds than the roughir stands is to increase the capacity of the mill, and to finish the material such a rate that it does not become too cool; this difference in speeds al makes it possible to work without an exceedingly large loop from one pa to the other.

249. Direct-connected drive. The best arrangement is to connect t motor direct to the mill, if the mill speed is such that this is feasible. general, the lowest speeds possible for direct-connection at 25 cycles are follows: 250 to 500 h.p., 125 rev. per min.; 500 to 1,000 h.p., 100 rev. per mi 1,000 to 2,000 h.p., 85 rev. per min.; 2,000 h.p. and upward, 70 rev. per mi

250. Geared drive. The first cost of slow-speed motors is high, and very large motors are not required, some speed-reducing arrangement generally used for slow-speed mills. The low power-factor of the slow-spee motor is a serious objection. Gearing has been used extensively for co necting motors to mills, and the use of cut double-helical gears makes po sible pitch-line speeds previously impracticable. Although the maintenan is increased, gears permit the installation of high-speed motor of go performance at low cost. The use of gears introduces losses and offsets th increased efficiency of high-speed motors, but the advantage of high powe factor is important. An important advantage of gear drive is that in th case of very slow-speed mills, the fly-wheel (Par. **254**) can be located on th pinion shaft and run at such a speed that comparatively small weight required. This is of particular importance in sheet mills, which run at approximately 30 rev. per min., as sufficient fly-wheel effect cannot be obtained to equalize the input properly if the fly-wheel is located on the mill shaft.

When connecting the motor to the mill, the fly-wheel (Par. **254**) shou be so placed that the shocks from the rolls are not transmitted to the mot The best location is on the mill shaft, but with very slow-speed mills it may be necessary to place the fly-wheel on the pinion shaft for the reason above mentioned.

When the fly-wheel is mounted on the pinion shaft, the gear must be pro portionately larger, as it transmits the peak loads. When the fly-wheel mounted on the mill shaft (Fig. 36), the gear need only be large enough t transmit the motor load. In practice, pitch-line speeds up to 1,500 ft. pe min. are used with plain spur gearing, and up to 2,500 ft. per min. wit double-helical gears. The best practice is to mount the gears in a substantia case and to run them in oil, which decreases the noise and reduces mai tenance.

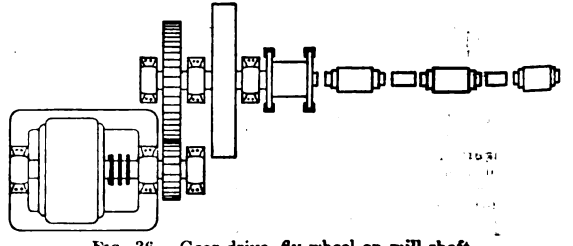


FIG. 36.—Gear drive, fly-wheel on mill shaft.

251. Rope drive is extensively used in steel mills where the mill-speed is suitable. Rope speeds up to 6,000 ft. per min. are used, the rope wheel acting as a fly-wheel for the mill. General practice does not differ from that of rope drive in other industries. Large fly-wheels are generally required to prevent rapid fluctuations in the amount of power transmitted from the motor and consequent whipping of the ropes. Belt drives are used only to a small extent in steel mills, usually where a number of stands are arranged in tandem to be driven from one source of power, the belt being passed

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around several pulleys. The present practice is to substitute gears for belts in this type of mill.

252. Reversing blooming mills cannot be driven directly by alternating-current motors, due to the difficulty of control, and to the unsuitable characteristics of such machines. Direct-current motors are used for driving the rolls, and are supplied with power from fly-wheel motor-generator sets, the field of the generator being varied and reversed to control the speed and the direction of rotation of the roll motors. The roll motors are always excited with the same polarity, and the reversal of the armature current of the generator reverses the rotation of the roll motor. The fly-wheel is used to equalise the input to the motor-generator set, and, in practice, limits the load in the line to about one-fourth of the maximum output of the generator.

253. Reversing rolling mills have been built with motors which exert as much as 16,000 h.p. on the rolls for short periods.

254. Fly-wheels. The function of the fly-wheel is to give up energy during the period when the load on the rolls is in excess of the capacity of the motor, and to store energy when the rolls are idle between passes. In rolling-mill practice, a speed variation of from 15 to 20 per cent. is permissible.

The energy available from the fly-wheel is:

$$\frac{W(V_1^2 - V_2^2)}{2g \times 550} \quad \text{(h.p. sec.)} \qquad (7)$$

where W = weight of fly-wheel in lb., V_1 = maximum velocity of wheel at radius of gyration in ft. per sec., V_2 = minimum velocity of wheel at radius

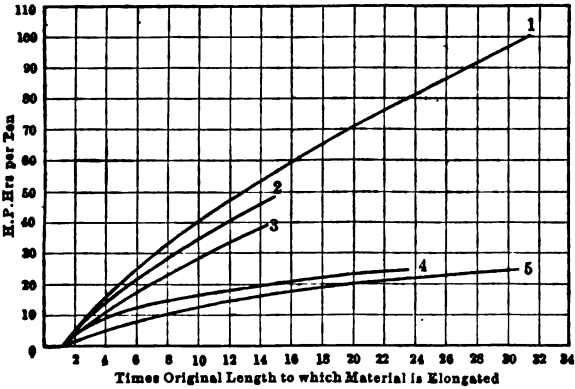


FIG. 37.—Curves showing average energy consumption of different types of mills.

Curve No. 1, rolling small billets of high-carbon steel to rods.
Curve No. 2, rolling billets to light rails.
Curve No. 3, rolling billets to flats and squares.
Curve No. 4, rolling ingots to billets.
Curve No. 5, rolling slabs to plates.

of gyration in ft. per sec., g = acceleration due to gravity = 32.2 ft. per sec. By properly arranging the control of the motor, the rate at which the energy is given up by the fly-wheel can be regulated, so as to limit the load on the motor to the average value, providing sufficient fly-wheel effect is available.

The majority of fly-wheels used on rolling mills are built of cast iron, and as a general practice, the limit of peripheral speed in such cases is 6,000 ft. per min., because higher speeds are not considered safe, owing to the uncertainty of the shrinkage stresses. By special construction to avoid such

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stresses, cast-iron wheels for a peripheral speed of 10,000 ft. per min. have been built with success. For moderately high speeds, cast-steel wheels are commonly used, the usual limit of peripheral speed being 12,000 ft. per min.; but in special cases cast-steel wheels run at speeds up to 22,000 ft. per min. Such speeds are dangerous if the material is not homogenous and free from initial stresses, but with proper design and annealing, they have proved successful. For speeds up to 30,000 ft. per min. fly-wheels have been built from discs cut from single plates, the plates being riveted together to form a solid wheel.

255. Factors affecting power requirements. The power required by rolling mills depends upon the following factors: (a) volume of metal displaced in a given time; (b) manner in which the section is changed; (c) temperature of metal during rolling; (d) class of material; (e) size of rolls. The determination of the best arrangement of motor and fly-wheel for any particular mill necessitates the analysis of the power required for each pass. The average output required can be obtained from Fig. 37, which shows **average energy consumption for different classes of materials.** The figures given are h.p. hr. per ton of metal rolled, plotted against elongation. To these figures should be added the friction of the mill, in order to obtain the motor load. The size of the motor may be determined from these curves, provided that the tonnage taken corresponds to the maximum that the mill will roll if working continuously, and that there is sufficient fly-wheel effect available to equalise the peak loads.

256. Motor rating and temperature rise. Rolling-mill motors are usually rated on a temperature rise of 35 deg. cent. and they have a continuous overload capacity of 25 per cent. with 50 deg. cent. rise and a 1-hr. overload capacity of 50 per cent. with 60 deg. cent. rise. With the knowledge now available of the power requirements, a standard temperature rise of 40 deg. cent. with a 25 per cent. overload capacity for 2 hr. is satisfactory, if the conditions are properly analysed.

257. Typical power requirements

Type of mill	Original section (in.)	Finished product (in.)	Tons per hr.	Peripheral speed of rolls (ft. per min.)	Size of motor (h.p.)	Fly-wheel effect at mill shaft in W^2*
Blooming mill	16×16×66	3×3	40	525 at 70 r.p.m	8,000 Max.	.....
Blooming mill	19×23×76	8×8	100	500 at 60 r.p.m	10,000 Max.	.....
Plate mill	8×28×48	¼×80	40	500	2,000	15,000,000
Billet mill	4×4×60	1¼×1¼	50	400	1,000	.....
Bar mill	9×4	1¼×1¼	7½	445	1,100	6,400,000
Bar mill	6×3	1¼×1¼	5	630	800	1,160,000
Sheet mill	¼×30×7	Sheets to 30 gage	8–24 gage	230	1,500	9,550,000
Sheet mill	¼×30×7	Sheets to 30 gage	10–24 gage	215	1,600	17,000,000
Rail mill	24×24 to 4×4	16 to 40 rails	.....	550	2–1,500	7,400,000
Rod mill	1¼×1¼	½ round	10	1,000	2–1,200	None

* W = Weight in lb.
Radius of gyration in ft.

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258. Energy consumption per ton of material

Type of mill	Original cross-section (in.)	Finished product (in.)	Tons per hr.	H.p. hr. per ton
Reversing blooming mill	20×20	8×8	95	21
Reversing blooming mill	16×16	3×3	40	42
Plate mill	6×30	¼×30	50	28
Plate mill	7×24	¼×24	70	16.5
Sheet mill	7×30×⅛	0.025	8	165
Sheet mill	7×30×¼	0.04	10	128
Rail mill	4×4	40 Rail	75	20
Billet mill	4×4	1¼×1¼	50	20
Rod mill	1¼×1¼	½ Round	20	60
Bar mill	4×4	1×1	15	48

259. Types of motors adaptable to rolling-mill practice. Alternating-current motors are used almost exclusively for driving rolling mills, direct-current machines being adopted only in a few installations of comparatively small capacity, or where there are special speed requirements.

Special types of direct-current and alternating-current auxiliary motors for steel-mill service have been developed, the principal characteristics of these machines being high overload capacity without injury, and great mechanical strength. Accessibility is also an important factor in order to facilitate rapid repairs. Mill motors are built from 5 to 150 h.p., being usually rated on a temperature rise of 75 deg. Cent. after 1 hr. operation. They are equipped with heat-resisting insulation, because they are often located near furnaces where the temperature of the motor even without load may be very high. The maintenance cost of such motors is approximately one-fourth that of the modified railway motors previously used. Full particulars of these motors can be obtained from the publications of the manufacturers.

260. Control. It is becoming general practice to use hand-operated controllers only for auxiliary motors up to about 30 h.p., larger machines being provided with magnetic-switch controllers. The principal characteristics of steel-mill controllers are simplicity, reliability in operation and ability to stand abuse. The special construction necessary to meet these conditions increases appreciably the cost of steel-mill controllers as compared with controllers for ordinary industrial service.

For motors driving main rolls, magnetic-switch controllers are generally used, the resistance being so arranged that various running points up to 15 per cent. slip may be obtained, in order that the motor will slow down on heavy loads and allow the fly-wheel to give out a part of the energy stored in it. Automatic slip regulators are now being adopted, in order to regulate the rate at which energy is delivered by the fly-wheel, thereby obtaining better equalisation of the load on the motor. Liquid regulators are used on account of their simplicity and small maintenance, as well as quickness in action and sensitivity.

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CEMENT MILLS

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PORTLAND CEMENT MANUFACTURE

262. Materials. The necessary ingredients, lime, silica and alumina, are generally obtained from two raw materials, in one of which the lime predominates and in the other the silica and alumina. The materials used in this country are: (a) cement rock and limestone; (b) limestone and shale or clay; (c) marl and shale or clay; (d) blast-furnace slag and limestone. About 80 per cent. of all Portland cement is made by combinations (a) and (b). The process using combination (c) generally employs the wet or slurry system of grinding, since the marl is dredged from swamps or underwater.

263. Process. Briefly stated, the process of manufacture consists in reducing the raw materials to a fine powder, mixing the ingredients in the correct chemical proportions as shown by analysis, burning to a clinker, and again reducing to a fine powder which is Portland cement. In a mill using the dry process, the buildings, departments and machines are arranged in approximately the following order, although there are many different types of machines in use to do the same work.

Departments	Machines
Quarry	Hoists, air compressors, pumps.
Raw mill	Crushers, dryers, intermediate grinders, automatic scales, fine grinders.
Coal mill	Crushers, dryers, fine grinders.
Kiln building	Kilns, blowers or fuel feeding apparatus.
Clinker storage	Cranes, cableways, conveyers.
Finishing mill	Intermediate grinders, fine grinders, or pulverisers.
Packing house	Automatic sacking machines, conveyers.

Also numerous elevators and conveyors in all departments.

264. Power requirements. Extensive tests and investigations have shown that the average power demand per bbl. of cement per day depends on many items, but is usually within the limits of from 0.75 h.p. to 1.5 h.p. at the switchboard. On this basis the energy consumption will be from 13.5 to 27 kw-hr. per bbl. Even with energy at 1 cent per kw-hr. it will be seen that the cost of energy is a very large part of the total value of the cement, which, for the United States in 1917 averaged about $1.35 per bbl. at the mill. In 1917 about 93 million barrels of cement were manufactured in the United States, although the capacity of the kilns installed is about 50 per cent. greater. A total capacity of more than 400,000 h.p. of electric motors is installed in cement plants and the percentage of electric power used is rapidly increasing and is now about 75 per cent. With the exception of the quarry and the crushers, and sometimes the coal house, all of the machinery in a cement plant is in continuous operation and at a nearly constant load; the load factor would be very nearly unity were it not for these portions of the plant, and is often from 80 to 85 per cent., based upon the ratio of average to maximum demand.

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265. Waste heat boilers. One of the most recent economies effected in cement production is the utilisation of the exhaust gases from the kilns for the generation of steam. Specially designed boilers are installed to utilise the gases from one or more kilns according to their size and arrangement. Experience has shown that in a mill using high efficiency prime movers the waste heat will supply approximately enough steam for the entire power equipments. A small steam boiler reserve is usually necessary to take care of variations in kiln operation or power requirements. The installation of waste heat boilers eliminates practically all coal used for power purposes with the result that the total coal used per barrel of cement is reduced from 30 to 50 per cent.

266. Motor characteristics. Induction motors either of the squirrel-cage or slip-ring type are used in practically all new installations, but synchronous motors in the larger sizes are used to a limited extent to give power factor correction. The simplicity and ruggedness of the squirrel-cage motor makes it admirably adapted for the severe and dusty service of cement mills. The bearings should be made dust proof. Ball and tube mills and others of similar characteristics are very difficult to start, and motors for such applications should have a starting torque of not less than twice the value of full-load torque. When synchronous motors are used for such drives friction clutches are required, but other types of motors should be designed to meet the conditions. Slip-ring motors are often used for large gyratory crushers, tube mills and other machines when the power required exceeds approximately 200 h.p., on account of the large starting current required by squirrel-cage motors. Speed variation is often desirable on kilns and dryers and such requirements are readily met by the use of slip ring motors with resistance designed for 50 per cent. speed reduction.

267. Jaw crushers are often used for secondary crushing, or upon clinker, and the following are typical ratings.

Jaw Crushers—Blake Type

Size of jaw opening (in.)	Weight of crusher (lb.)	Capacity per hr. according to size				Driving pulley			Horse power (aver.)
		Tons	In.	Tons	In.	Diam. (in.)	Face (in.)	Rev. per min.	
10× 7	7,550	6	2	2½	1	24	7½	250	7½
15× 9	12,000	16	3	8	1½	30	8½	250	10
20×10	21,500	38	4	19	2	36	13	250	20
24×15	38,000	60	5	25	2½	42	16½	250	25
36×24	68,000	130	6	70	3	Pulleys to suit conditions		250	75
42×40	130,000	225	8	130	4½			250	100
60×48	205,000	290	9	180	5			200	150
84×60	400,000	450	11	280	7			100	200

Champion Crushers (American Road Machinery Co.)

Size no.	Size of jaw opening (in.)	Weight of crusher (lb.)	Tons per hr. according to material and feed	Driving pulley			Horse power
				Diam. (in.)	Face (in.)	Rev. per min.	
3	7½×13	5,500	8 to 12	38	8	170	12
4	9 ×15	8,800	12 to 18	48	9	155	15
4½	10 ×20	12,500	16 to 24	50	10	150	18
15	11 ×22	12,000	18 to 26	48	9	150	20
5	11 ×26	20,000	24 to 35	60	9½	140	25
20	18 ×50	60,900	70 to 100	72	12½	105	50 to 60

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268. Gyratory crushers. The following table gives the ratings of Gates crushers; other makes of similar size have approximately the same power requirements.

Gates Gyratory Crusher—Style "K"							
Size no.	Size of openings (in.)	Weight of breaker (lb.)	Capacity per hr. in tons (2,000 lb.), varying with material	Driving pulley			Horse power
				Diam. (in.)	Face (in.)	Rev. per min.	
4	8×30	22,000	15 to 40	32	12	400	14 to 21
5	10×38	32,800	30 to 70	36	14	375	22 to 30
6	12×44	48,000	50 to 90	40	16	350	28 to 45
7½	14×52	68,000	80 to 120	44	18	350	50 to 75
8	18×68	103,000	130 to 150	48	20	350	70 to 110
9	21×76	155,000	250 to 300	56	20	300	100 to 150
		Several larger sizes are manufactured					

269. Rotary dryers. For the average size of dryer, 5 ft. diam. by 50 or 60 ft. long, revolving at 2 to 5 rev. per min., from 10 to 20 h.p. is required. This varies with the construction of the dryer, the method of the drive and the speed of rotation.

270. Ball mills

Gates Ball Mills				
Size no.	Weight without charge of balls (lb.)	Weight of charge of balls (lb.)	Cap. on Portland cement clinker to 20 mesh	Horse power
7	29,500	3,000	12 to 16 bbl. per hr.	30 to 40
8	41,100	4,500	18 to 24 bbl. per hr.	40 to 50

The F. L. Smidth Co. Kominuters are similar to ball mills, and the three sizes, No. 53½, 66, and 88 require approximately 30, 75 and 100 h.p. respectively.

271. Williams mills. These are of the swinging-hammer type, and are made in various modifications for pulverizing coal, clay, clinker, etc. The ratings of the coal and cement crushers are as follows:

Coal crushers			
Size no.	Pulley dimen. (in.)	Rev. per min.	Horse power
1	20×15	1,000	20
2	20×15	1,000	30
3	20×15	1,000	50–60
4	24×18	1,000	75
5	24×20	1,000	100
8	30×32	750	250
Cement grinders			
Size no.	Pulley dimen. (in.)	Rev. per min.	Horse power
1	16×12½	1,500	20
2	16×12½	1,500	25–30
3	20×15	1,000	30–60
9	30×20	720	150–200

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272. Type of drive. For satisfactory service and long life, a motor should not be subjected to severe vibration. Either belts or flexible couplings are able to absorb the vibration of the grinding machinery, but the dust causes rapid deterioration of belts and, therefore, the best practice is direct-connection wherever possible. The countershafts of ball and tube mills rotate at about 180 rev. per min. and, on 25-cycle circuits, motors at this speed may be direct connected throught flexible couplings. Motors should, whenever possible, be placed in a separate room, the shafting extending through into the mill proper. For Fuller, Griffin, or other vertical-shaft mills, special belted vertical motors can be obtained which are more satisfactory than horizontal motors with quarter-turn belts.

273. Kent mills. This mill (made by the Kent Mill Co.) is in very extensive use both as an intermediate and a fine grinder. Being of the roll and ring type it can be started with comparative ease, and a 40-h.p. motor is usually supplied to drive the mill with its elevator and screen. The pulleys on the mill are 36 in. × 8 in., and 64 in. between centres, running at about 200 rev. per min. Motors with double-extended shafts make a simple and satisfactory drive.

274. Tube mills of 5, 5.5, 6 and 7 ft. diam. by 22 ft. long are now in common use in cement mills. The required power varies with the charge of pebbles and the feed, but with flint pebbles averages 100, 125, 150 and 200 h.p., respectively, for the above mills. The present day tendency however is toward larger mills requiring 300 to 500 h.p. For belt drive, motors from 480 to 690 rev. per min. are used, while for coupled drive 160 to 180 rev. per min. is customary. The F. L. Smidth No. 16 and 18 tube mills are usually driven by 100-h.p. and 150-h.p. motors, respectively. When "cylpebs" (short cylindrical pieces of steel) are added to a tube mill the power required is increased 20 to 30 per cent.

275. Fuller mills. The Lehigh Car Wheel & Axle Works have on the market three sizes of Fuller mills, known as the 33 in., 42 in. and 57 in. The smaller mill is used principally for coal, while the two larger sizes are adapted to pulverising either raw material or clinker. The power requirements are given in the following table.

Size of mill (in.)	Pulley			Horse power
	Diam. (in.) Max.	Face (in.)	Rev. per min.	
33	45	12	210	25–40
42	54	18	160	75–90
57	75	23	130	150–200

Vertical belted motors make the best drive for these mills.

276. Griffin mills. These mills which are of the vertical type are manufactured by the Bradley Pulveriser Company. Since the driven pulley is above the mill they are often driven in groups, but individual drive with vertical belted motors is desirable especially for the larger sizes of mills.

Type of mill	Pulley		Horse power
	Diam. (in.)	Rev. per min.	
Junior Giant Griffin.....	30	190–200	30–35
Giant Griffin.....	42	160–170	75–85
Bradley 3 Roll.....	42	160	50–60
Bradley Hercules.....	72	125	250–300

277. Bonnot pulverizer. Although this is a vertical mill, it has a horizontal pulley running at about 215 rev. per min. Only one size of mill is manufactured; this requires from 75 to 85 h.p. Either a belted or a coupled motor may be used.

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278. Aero pulverizers. These reduce crushed coal to an impalpable powder, and blow it into the kiln, mixed with the correct amount of air for combustion.

Aero pulverizers						
Size no.	Weight (lb.)	Height (in.)	Floor space (in.)	*Normal capacity of soft coal (lb. per hr.)	Rev. per min.	Horse power
A	1,800	28½	61½ × 27½	600	2,000	10
B	3,500	38½	77½ × 29	1,000	1,600	15
C	4,200	51½	78½ × 29	1,500	1,500	20
D	4,400	44½	78½ × 29	2,000	1,400	30
E	5,600	46½	97 × 33	2,800	1,400	40

* The capacity may be increased 25 per cent. or decreased 50 per cent without material loss of economy.

279. Kilns. The size of kiln in greatest favor at present is about 7 or 8 ft. in. diam. by 125 to 135 ft. long. However, many shorter kilns are in use and a number have lengths of 150 ft. or longer. Pulverized coal is used as fuel in over 80 per cent. of the kilns, and oil gas in the remainder. To burn the clinker properly, a speed adjustment ratio of 2 to 1 is usually necessary, and slip-ring motors with controllers are required. For 7-ft. × 100-ft. kilns an average of 15 h.p. is required, and from 20 to 40 h.p. is required for 8-ft. × 125-ft. kilns.

COAL MINING

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DEVELOPMENT OF POWER PRACTICE

280. Haulage and hoisting. The early mines in the United States generally consisted of a hole in the side of a hill extending back a few hundred feet into the hillside. The coal was mined entirely by hand, a process known as "pick mining," and the small cars were pushed to the entrance where the coal was dumped on loading platforms. As the distance became greater and adverse grades were encountered, it became necessary to obtain a new source of power, and the time-honored mule was found most satisfactory. At the present time this method of traction has practically disappeared from main haulage work, and is also being rapidly replaced by mechanical processes of gathering. When shaft mines were developed, a power system was necessarily employed in the hoisting of coal, men and material. Steam was first used and a few compressed-air hoists followed later. Electric hoisting practice has, however, found a firm footing, and a great many old mines are to-day electrifying their hoists. (Par. **91**).

281. Pumping (Par. 296). Very few mines can be laid out to be self-draining, and pumping becomes necessary as soon as they are opened. The early power pumps were steam-operated, and this type appears in a great many of the pumps of to-day. The inherently poor economy of steam or air pumps, and the large losses in long pipe lines make this type of installation compare very poorly with electrically driven pumps.

282. The ventilating systems (Par. 297) were operated by steam for many years. The electric motor is, however, rapidly supplanting the steam engine and is establishing for itself a remarkable record in regard to flexibility, continuity of operation and the economical use of power.

283. Mining machines (Par. 298). Originally coal was all pick-mined but it soon became evident that power must be used to mine the coal, as an insufficient amount of labor was available to care for the rapidly increasing output. The first mining machine was the compressed-air puncher-type followed later by the compressed-air chain-type. Various kinds of electric

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mining machines are in use to-day, and many new types are being developed. The particular design of machine which should be used to meet a particula set of conditions, can be determined only by experience.

284. For auxiliary power outside of the mine (Par. 296), such as power for shops, pumps, etc., steam engines have been largely used; and to substitute an electric motor is usually a comparatively simple matter.

285. Safety specifications. Various countries and each of the mining states of this country have mining codes which deal with the manner of installing electrical apparatus in mines and give general safety rules. The best reference for Rules for installation of electrical equipment in mines is in Technical Paper No. 138 issued by the U. S. Bureau of Mines.

ENERGY SUPPLY

286. The generators are generally of the direct-current, 250-volt or 500-volt types. These generators should be compounded about 10 per cent., and should be capable of withstanding momentary overloads of from 50 to 100 per cent. Standard machines are built for 225-volt to 250-volt service, for 250-volt to 275-volt service and from 500-volt to 550-volt service. The higher voltage of 500 has an advantage over 250 volts in that very much less copper is needed and greater distance can be covered. The danger is, however, considerably greater, and many states are legislating against the use of over 300 volts underground. Compounding is desirable due to the long lines that are required in reaching the workings. The type of load is such that heavy short-time peaks frequently occur.

287. Predetermination of generator capacity. When a mine is small and electric power is used for only one or two locomotives, the capacity of the generator will be determined entirely by the peak loads. For instance, if the load were to consist of two 10-ton locomotives each having two 50-h.p. motors, the conditions will be as follows: 1-hr. rating of motors, 200 h.p.; continuous rating of motors about 80 h.p.; maximum load with both locomotives starting 300 h.p. To compensate for the line drop and efficiency, 1 kw. should be allowed at the switchboard for every horse-power at the machine.

It will be seen from the above that on a heating basis, an 80-kw. generator can be used. This machine, however, could not take care of a load of 300 kw. The generator should have a capacity of not less than 150 kw. If old second-hand generators and engines are installed, it will be necessary to provide for a capacity of from 200 to 250 kw., as there would be a lack of overload capacity. The efficiency of power generation will not be very high, since the unit will be carrying a small load a considerable portion of the time. Excellent examples of load diagrams showing the low average and the high peak loads obtained at a coal mine power plant are shown in a paper presented before the A. I. E. E., April, 1913, by Wilfred Sykes and Graham Bright.

If we were to add to the above a third locomotive, a pump load of 50 h.p., a fan load of 50 h.p., and a cutting load of four 25-h.p. cutters, we would have the following conditions:

One-hour rating of motors.....	300 + 50 + 50 + 100 = 500
Continuous rating of motors.....	120 + 50 + 50 + 40 = 260
Maximum load of.	400 + 50 + 50 + 100 = 600

For the maximum locomotive load, two locomotives can be considered as starting, each developing 150 h.p., and one running taking 100 h.p. There will, no doubt, be a diversity among the machines, so that the actual peaks will not be over 550 h.p. The generator capacity should be 300 kw., preferably divided between two units of 150 kw. each. From these figures it will be seen that, for the larger plants, the generators can be operated more nearly at their continuous capacity.

At larger mines, or where one company operates a group of mines, a central alternating-current generating system is frequently installed. Energy is generated at 2,200 volts, 3 phase, 60 cycles, and is either transmitted to substations at 2,200 volts, or stepped up to 6,600 volts or 11,000 volts. Motor-generator sets or rotaries are used at the substation to transform the alternating current to direct current. Motor generator sets can be readily over-compounded if desirable while rotaries are best operated flat compound. In determining the capacity of the central plant, the machine and line losses must be taken into account in determining the size of the main generating

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units. These losses will average from 15 to 20 per cent. The capacity of the central plant will not be the sum of the individual substations, as there will be considerable diversity. The diversity factor will range from 1.2 to 1.5 to 1.

288. Design and advantages of mines using purchased energy. When central-station power is used, the power application is very much simplified. For haulage, cutting and inside pumping, a motor-generator set or synchronous converter is used. The motor-generator sets are generally of the synchronous type, owing to the power-factor correction which can be obtained with the synchronous motor. This high power-factor will compensate for the lower power-factor obtained on the induction motors used for driving fans, pumps, and tipple or breaker machinery. The substation can be a very simple structure and, in a great many cases, the old generating room can be used. The care of a substation is an extremely simple matter when compared with an isolated plant. For fans, compressors, outside pumps, tipple and breaker machinery and machine or blacksmith shop drive, the squirrel-cage motor is best adapted, as regards first cost and upkeep. This apparatus can be operated at all times independent of the motor-generator set which, in many cases, operates only 8 or 10 hr. per day.

MOTOR CIRCUITS

289. Permissible voltage drop for haulage, gathering and cutting (for good operation), should not exceed 20 to 25 per cent. at maximum load.

290. Diversity in peak-load calculations. **See Par. 287.** Where several locomotives and cutting machines are supplied from one feeder, the maximum load is obtained by estimating the number of machines that may be running at one time. It is seldom that two locomotives will start at the same time where only three or four are in use. In practice, a locomotive will not operate at full-load more than one-fifth of the time. The same is true of mining machines, and the maximum load should be estimated from the local conditions that exist at each mine.

291. Construction methods and costs.* Trolley and feed wire should be installed in a substantial manner and protected from contact with men, and mules at cross-overs. The total cost, including labor and materials for erecting a 0000 trolley wire in an anthracite mine will range from $1,000 to $1,400 per mile, and from $650, to $900, in a bituminous mine, depending upon the nature of the roof. Outside of the mine, the cost per mile will range from $1,200 to $1,600. Number 0000 feed wire will cost, erected, from $900 to $1,200 per mile inside of the mine, and from $1,100 to $1,500 outside of the mine for an anthracite mine. The cost of 0000 feed wire in a bituminous mine will be about the same as for the trolley wire. The rail return is generally much neglected. The bonding should be frequently checked with a bond-testing instrument and cross bonds should be installed at about every 200 or 300 ft. All switches, frogs, and cross-overs should be bonded around and cross-bonds should be placed on each side. Any water, or air pipes should be well bonded to the rail, especially near the main entrance, in order to obtain the benefit of an extra return circuit and to prevent electrolysis. The total cost of bonding a track (rails varying from 30 to 50 lb. per yd.) with No. 00 bonds including cross-bonding, will be about $350 per mile, including labor and material. The total cost using No. 0000 bonds will be about $400 per mile. Electrically welded bonds are proving very superior to the compressed or soldered bond and in many cases are less expensive to instal.

The haulage and cutting circuits should be kept separate where possible, but should be arranged to connect together in order to help out one another in emergency cases. In the larger mines, the feeders can be separated in order that local line trouble will not shut down the entire mine. However, in some large mines, it is the practice to connect everything solidly, and in case of trouble the circuits are held closed and the source of trouble removed by literally burning it out.

292. Lighting circuits both inside and outside are generally taken from the haulage or cutting feeders. Incandescent lamps for either 110 or 250 volts are used, with as many in series as necessary.

* Based on 1915 prices; add 50 per cent. to above figures for 1922.

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MOTOR APPLICATIONS

293. Compressor motors. See Par. **174** to **192.** Where compressed air is used, motor-driven compressors can be applied to advantage. For small compressors, the best type is that used by street railways for supplying compressed air for brake systems. For larger compressors a synchronous-motor drive is most used because of the high-power factor obtainable thereby. Compressor motors are often operated at 80 per cent. leading power-factor in order to compensate for the lower power-factor due to the induction motors which are used to drive fans, pumps and tipple or breaker equipment. With a synchronous motor drive, an unloading device must be used on the compressor; this prevents the motor from being loaded until it has reached synchronous speed.

294. One great advantage of electrically driven air compressors is that they can be installed at the most convenient location. Small auxiliary compressors can be easily located inside of the mine at the end of long pipe lnes where it is difficult to maintain normal pressure.

295. Types of adaptable motors. For tipples, breakers and shops, considerable power is often required for crushers, screens, elevators, washers and machine tools. When direct current is employed, a compound-wound motor is best adapted, and is sometimes built totally enclosed in order to avoid the effects of coal dust. The motors should be continuously rated, as the load is fairly constant. A shunt-wound motor is best adapted for shop purposes, as its speed is more nearly constant under varying loads. When power is purchased, all outside motors can be of the alternating-current type, so that the motor-generator sets, or synchronous converters, need only supply the haulage, cutting, inside lighting and pumping. Where very heavy starting loads obtain, the wound-rotor induction motor with drum type controller should be used. Where only moderately heavy starting torques are required, the squirrel-cage motor is best adapted. The rotor characteristics of this motor will depend upon the character of the load. This is by far the simplest and most rugged motor built, the control also being very simple. Where starting requires a low torque, a low resistance end-ring can be used; where high starting torques are required, a fairly high-resistance end-ring should be used. The cast end-ring has solved all end-ring troubles which were once so prevalent.

296. Pumping. For inside pumping the reciprocating duplex or triplex pump is most used for the smaller sizes. The centrifugal pump is not so well adapted for moving about and for use under various heads. The capacity of the motor can be readily determined by the amount of work to be done, assuming an efficiency of 50 to 60 per cent. for centrifugal and 70 to 75 per cent. for reciprocating pumps. See Par. **155** to **173.**

297. Ventilation. Mine fans are inherently low-speed machines and are very well adapted for direct connection to a steam engine. For economy in first cost and operating cost an electric motor is inherently a high-speed machine, usually requiring some speed-reducing device in such an application. Belting seems to be the most popular method, although gearing, chain drive and even rope drive, are used occasionally. See Par. **193** to **212.** A. C. squirrel cage motors for small fans and woundrotor motor for large fans are most popular. The synchronous motor is being proposed and will no doubt find many applications.

298. Machine mining. Pick mining is a rather slow and laborious process of mining coal, although a large portion of the coal is still mined by this method. Machine mining has become a necessity owing to the increasing demand for coal and the limited supply of labor. Punchers and chain machines are the two types generally used. **Punching machines** were first driven by compressed air, and most of the mach nes of this type are still operated in this manner. The electric puncher consists of a motor-driven compressor attached to the cutting mechanism, so that compressed air really is used to operate the puncher. This machine has the advantage of electric transmission, but is heavier and more expensive than the straight-air puncher.

The **chain machine** is the most rapid of all mechanical cutters. The chain cutter will require a motor having an intermittent rating of from 20 to 40 h.p., while the pneumo-electric machine will require a motor rated from 10 to 15 h.p. As a rule direct-current compound-wound motors are used to operate coal-cutting apparatus. Alternating-current motors are being intro-

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duced for both punching and cutting machines and have been very successful. They, however, require a separate power circuit consisting of two feed wires with track return. They possess the advantages of simplicity of construction and less danger of the workmen coming in contact with live parts.

298(a). Loading Machines.—On account of the high cost and scarcity of labor the Loading Machine is being rapidly developed. These machines require about three men to operate and will load 100 to 400 mine cars per day. The power equipment is generally direct current consisting of 2 or 3 motors having a total horsepower rating of about 75 on the larger machines.

LOCOMOTIVES

299. Locomotives for main haulage and gathering are of the direct-current type, designed to operate on 250- or 500-volt circuits. The series type of motor is invariably used as it has the best speed-torque characteristics for the service. The service is somewhat similar to street-railway conditions and the same general methods are used to determine the weight and capacity of the equipment.

Mine locomotives are built in weights ranging from 4 tons to 35 tons and gages ranging from 18 in. to the standard of 4 ft. 8.5 in. The wheels may be cast iron with chilled tread, steel tired, or rolled steel. Gathering locomotives are built to replace mules; these weigh from 4 to 8 tons with equipment varying from two 10-h.p. motors to two 40-h.p. motors.

300. Locomotive-adhesion and weight calculations. The cast-iron wheel will afford a running coefficient of adhesion of 20 per cent., and a starting coefficient of 25 to 30 per cent. when sand is used. The steel-tired or rolled-steel wheel will have a running coefficient of 25 per cent. and a starting coefficient of 30 to 33.33 per cent. with sand. The above figures are conservative and can be easily obtained with fair rail conditions. The weight of locomotive is determined by the following formula:

$$T(30+20G)+20GW=400W. \text{ for cast-iron wheels,}$$
$$=500W. \text{ for steel wheels.}$$

Where T = weight of trailing load in tons. The item 30 is the friction in lb. per ton for the trailing load on the level and is the average value obtained by test for small mine cars. The expression $20G$ is the pull necessary to overcome gravity, G being the grade in per cent. W = weight of locomotive in tons. The item 400 is 20 per cent. of 2,000 lb. for cast-iron wheels. The item 500 is 25 per cent. of 2,000 lb. for steel wheels.

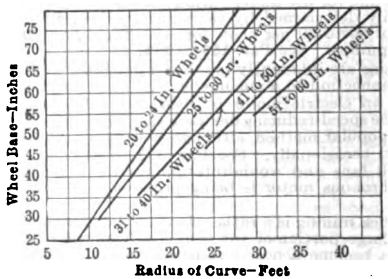


FIG. 38.—Relation of wheel base to radius of minimum curve.

A margin over 20 and 25 per cent. for starting with sand is available to take care of the extra tractive effort necessary for accelerating the load and locomotive when starting. See Sec. 16.

301. The track-curve resistance can, as a rule, be neglected, since the length of the average mine trip is many times that of any of the curves. For gathering, the curves may have a vital influence. In general, *each 1 degree of curvature adds ½ lb. per ton to the friction.* The ability of a locomotive to negotiate a curve depends upon the wheel base and size of wheel. The curves of Fig. 38 show a minimum radius of curve that any locomotive with a certain wheel base and size of wheel can negotiate. These values are conservative and are based on standard wheel flange and track play. With a liberal spread, the value of wheel base can be safely increased from 25 to 50 per cent.

302. Braking. In some cases the problem of braking becomes most important and the weight of the locomotive is determined by its ability to

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hold back a loaded trip on a certain grade. If a runaway would result in serious damage, then a smaller coefficient should be assumed than would be appropriate for pulling a load up a grade. With cast-iron wheels the coefficient for braking should not be over a value from 15 to 18 per cent. and for steel wheels 18 to 20 per cent. Care should be taken that wheels do not become too hot; this may break a cast-iron wheel, or cause a steel tire to slip. For retarding a trip down a grade, the formula of Par. 300 will be changed to:

$$T(20G-20)+20GW = (300 \text{ to } 360)W. \text{ for cast-iron wheels,}$$
$$= (360 \text{ to } 400)W. \text{ for steel wheels.}^*$$

303. The friction of the average mine car is about 30 lb. per ton. New cars in good condition may have a resistance very much less than 30 lb., but the friction increases with the age of the car, and may reach 40 to 50 lb. per ton. Roller bearings when kept in good condition will have a fairly low resistance, but unless good care is taken of them, their frictional resistance will rise rapidly.

304. Selection of proper rail weight. For each given weight of rail there is a corresponding maximum weight of locomotive which should not be exceeded for satisfactory operation. The following table has been prepared by the Baldwin Locomotive Works and represents the best modern practice.

Weight of locomotive (tons)	Weight of rails (lb. per yard)
4 to 6	16
6 to 8	20
8 to 10	25
10 to 13	30
13 to 15	40
15 to 20	50

If a heavier locomotive is desired than is shown in this table, tandem units are often applied.

305. Rating of locomotive motors. Although the motors of a mine locomotive are given a 1-hr. rating, it is the average heating that determines the capacity for all-day service. This heating is proportional to the square of the current. The average of the square of the current will give a squared value, the square-root of which is really the capacity of the motor for all-day service. This value is known as the square-root of the mean-squared current. It is obtained by finding the different values of the current for one motor throughout a round trip. These current values can be obtained from the characteristic motor curve of the particular motor used. After the weight of the locomotive has been determined, one of the standard motors for this weight is selected and calculations made to determine if it is of the proper capacity. The total tractive effort per motor is determined for each grade, allowing 20 lb. per ton for the friction of the locomotive. For each total tractive effort the current and speed are obtained from the curve, and the time is calculated. By squaring each current value and multiplying by the time, we have the sum of the products of various squared values of the current, multiplied by the time. This summation should be increased by from 5 to 10 per cent. to make allowance for acceleration and switching movements at each end. The final value is then divided by the total time, and the square-root extracted. The characteristic curve gives the continuous current capacity, which can be compared with the final result obtained.† Where the exact conditions are not known, as is generally the case, the common accepted practice is to allow 10 H.P. per ton weight of locomotive. This question should however be checked since the real capacity of a locomotive is the continuous rating of the motor and a motor of poor design may have a high one hour rating and a low continuous rating.

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* The car friction should be taken at 20 lb. for descending trips.

† For a more detailed explanation of the determination of weight and equipment of a mine locomotive see article, *Electric Journal* of March, 912, entitled "The Determination of Weight and Equipment of a Mine ocomotive," by Graham Bright. (This article gives an example with complete set of calculations.) Also see *Coal Age*, issues of March 6 and March 0, 1915.

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306. An electric reel is sometimes applied to a gathering locomotive s that it can be taken into rooms where no trolley wire is erected. This re may be chain driven from one of the axles or motor driven from a sma independent special motor which maintains a constant pull on the cable This cable may be single-conductor or double-conductor, depending upo the track conditions. A No. 4 A.W.G. cable is generally used.

307. A traction reel can also be supplied on a gathering locomotive. consists of a small motor-driven crab with from 300 to 400 ft. of steel cabl This type of reel is used where the room grades are very steep, and are drive to the dip.*

308. The storage battery locomotive is used extensively in gatherin service. There are three types of storage batteries available which a satisfactory for application to locomotives. These types are the Edison alkaline, the ordinary lead acid battery and Iron-Clad Exide type MV lea acid. The overall efficiency of conversion of the electrical output at th battery terminals to the mechanical output at the wheels will vary from 60 to 72 per cent. Assuming the overall efficiency to be 67 per cent., th watthours per train-mile is equal to the product of the total tractive effort times three ($w.h.p.t.m. = TE \times 3$). The tractive effort can be calculated by assuming the frictional resistance of the cars to be 30 lb. per ton, and o the locomotive, 20 lb. per ton, making a further allowance of 20 lb. per to for each per cent. grade, if any grades are involved. To estimate the batter capacity required for a given service, the entire haulage should be subdivided into as many sections as there are different characteristics. By calculating the tractive effort and distance for each section, the watthours for each sec tion can be obtained from the formula mentioned before. The summation of the watthours of all the sections will give the watthours of total batter capacity required for the service. The proper battery may be selected from the storage battery manufacturer's tabulated data. If the manufacturer's data specify the rated capacity in ampere hours, the ampere-hour service capacity may be obtained by dividing the calculated watthour capacity by the average voltage of the battery, assuming the average service discharge voltage of an Edison battery to be 1.1-volts per cell and of a lead battery 1.95 volts per cell. The Edison battery is rated on a 5-hour dis charge basis and the Philadelphia and Iron-Clad Exide batteries on a 6-hour discharge basis. Where the total elapsed time of discharge is not less than six hours, the rated capacity of a lead battery will be available for service.

Great care should be taken in making Storage Battery Locomotive applications and it will be found that many storage battery applications should have been trolley type. (Refer to Article on Storage Battery application to be printed in *Coal Age* in near future by M. F. Packard).

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REFRIGERATING PLANTS

BY AUGUSTUS C. SMITH

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310. Motors adaptable to refrigerating service. Ammonia compressors and auxiliary apparatus in refrigeration plants may be driven either by direct-current motors or by alternating-current motors. The flexibility of speed control of the direct-current motor offers an advantage, but the possibilities of speed control of the induction motor together with the characteristic advantages of this type are sufficient reasons to justify its selection where alternating current is available. If variable speed is not required, synchronous motors may be used.

311. Motor speeds and speed control. Motors for the operation of ammonia compressors should be of the variable-speed type, so that where the operating conditions require it, suitable speed control can be secured. Compressors of 50 tons capacity, and over, are operated usually at about 70 rev. per min., so that a belted motor of 500 rev. per min. or less, is desirable. When the compressor is of high speed type the motor can be direct connected.

312. Multispeed motors. With the two-speed motor, the compressor can be operated at full speed and at half speed; while with the three-speed motor, it can be operated at full speed, two-thirds speed and one-third speed. This method of speed control, however, provides for changes in the compressor at fixed and predetermined steps only, and does not, therefore, provide for the flexibility in speed control necessary to meet the usual requirements in the operation of refrigeration machines.

313. With the slip-ring type of motor and resistance speed control, flexibility of operation equivalent to that of the steam compressor is attainable. The power-factor of this motor remains practically constant at all speeds, but the efficiency falls off with the reduction in speed; operating the compressor continuously, at reduced output, with this type of motor, is therefore uneconomical from a power-consuming standpoint.

314. Plant duplication. In plants where it is necessary materially to reduce the output, during certain periods of the year, it is desirable to employ more than one compressor unit. This is especially true in large refrigeration plants, where the total compressor capacity should be divided among individual units, properly proportioned according to the required operating conditions.

315. The standard rating for ammonia compressors is based on 15 lb. suction pressure, 185 lb. condensing pressure, and condensing water at 70 deg. Fahr. (21 deg. Cent.). The power necessary to drive a compressor varies directly with the operating pressure, the horse-power being determined by indicator card.

316. Power requirements per ton. Ammonia compressors operated at 15 lb. suction pressure and 185 lb. condensing pressure, having a rated capacity over 5 tons of refrigeration per 24 hr., require about 1.5 h.p. per ton of refrigeration; compressors having from 5-ton to 1-ton capacity, operated under like conditions, require from 1.5 h.p. to 2 h.p. per ton. Increasing the above pressures to 25 lb. suction, and 200 lb. condensing pressure, would increase the power necessary to operate the compressor about 16 per cent.

317. Varying pressures and output requirements. In the daily operations of a refrigerating plant, it is frequently necessary to operate a compressor at increased pressures. In some localities during warm weather

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the temperature of the condensing water will exceed 70 deg. Fahr. (21 deg. Cent.), and during extremely warm weather it may be necessary to force the compressor beyond its rated capacity in order to meet unusual requirements, all of which require increased power. For compressors of 50-ton rated capacity and smaller, about 25 per cent. additional motor capacity should be provided for these possible excessive operating conditions; for larger compressors, from 15 to 25 per cent. additional motor capacity should be provided, depending upon the local and probable operating conditions of the plant.

318. Classification of ice-making plants. Ice-making plants may be divided into two classes: those making ice from **distilled water**, and those making ice from **raw, or natural water.** The former method uses the **can system**, while the latter may use either the can system, or the **plate system.** The compressor-room equipment for an ice plant of equivalent capacity is the same for all of these methods, except for the plate system, where about 15 to 20 per cent. more compressor capacity is required.

319. Operating data on 90-ton can-system ice plant using distilled water

Month	Maximum input (kw.)	Input (kw-hr.)	Tons of ice made
January	115	92,530	2,033
February	102	65,080	1,493
March	97	71,870	1,737
April	192	133,550	3,055
May	209	139,550	3,742
June	230	145,686	3,291
July	218	157,640	3,657
August	230	156,700	3,579
September	219	160,250	3,408
October	205	154,090	2,989
November	112	76,460	1,792
December	122	91,210	2,226
Total	.....	1,444,616	33,002

320. Equipment of plant using can system. The compressor-room equipment in this plant (Par. **319**) consisted of two vertical 16-in.×24-in. double-cylinder single-acting ammonia compressors of 70 rev. per min., at full-speed. Each of these compressors had a rated capacity of 45 tons of ice per 24 hr., when operated at 15 lb. suction pressure and 185 lb. condensing pressure, with condensing water at 70 deg. Fahr. (21 deg. Cent.). Each was belt-driven by a 175-h.p., 500-rev. per min., 3-phase, 25-cycle, 2,200-volt, variable-speed, slip-ring induction motor. The speed control consisted of a 13-step drum controller, and iron-grid resistance of sufficient capacity to permit the continuous operation of the motor at any speed from full speed to one-half speed continuously.

There was also installed in the compressor room a 6-in.×6-in. ammonia compressor having a capacity of about 4 tons of refrigeration, which was operated by a 10-h.p., 750-rev. per min., 3-phase, 25-cycle, 440-volt, variable-speed induction motor. This compressor was used for pumping out the ammonia system, and also was used, in connection with repairs, for testing, thus avoiding the necessity for operating the large compressors for these purposes.

The auxiliary and tank room equipment was all operated by 3-phase, 25-cycle, 440-volt induction motors consisting of the following: 1 condenser water pump, 25-h.p., 750-rev. per min., variable-speed, belted motor; 4 brine agitators, 5-h.p., 750-rev. per min., constant-speed, direct-connected motors; 1 distilled water pump, 5-h.p., 750-rev. per min., variable-speed, belted motor; 1 soft-water pump, 5-h.p., 750-rev. per min., variable-speed, geared motor; 1 boiler feed pump, 5-h.p., 750-rev. per min., variable-speed, geared motor; 1 water-softener mixer, 1-h.p., 750-rev. per min., constant-speed, belted motor; 2 cranes, 3-h.p., 750-rev. per min., variable-speed, geared motor.

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321. Operating costs of plant using can system. The average consumption of power in this plant (Par. 311) was 44 kw-hr. per ton of ice, while the other items of expense were: engine and boiler room labor per ton, 31 cents; fuel per ton, 19.50 cents; tank-room labor per ton 25.10 cents.

322. Equipment of plant using plate system. While the compressor-room equipment in both distilled-water plants and raw-water plants is practically the same, the auxiliary equipment differs, depending upon the type of plant, and the system used. The auxiliary and tank-room equipment of a raw-water plate plant electrically operated, and having a rated capacity of 100 tons of ice per 24 hr., may be taken as an example. In this plant all the motors are of the 3-phase, 25-cycle, 220-volt, induction type. A centrifugal condenser-water pump, direct-connected to a 6-h.p., 1,500-rev. per min., constant-speed motor is used to supply excess water to the condenser in hot weather, when the natural flow of city water supply is insufficient. A brine pump, belted to a 2-h.p. 750-rev. per min., constant-speed motor is used to circulate warm brine around the plates in order to loosen the ice. A rotary blower, belted to a 7.5-h.p., 750-rev. per min., constant-speed motor is used to agitate the water in the tanks. The rest of the equipment consists of 3 cranes, each equipped with one 5-h.p. and one 3-h.p., 750-rev. per min., variable-speed motors; 2 tilting tables, each geared to a 2-h.p., 1,500-rev. per min., constant-speed motor; 1 30-in. circular ice saw, operated by chain drive from a 3-h.p., 1,500-rev. per min. motor; 1 ice elevator, operated by and geared to a 3-h.p., 1,500-rev. per min. motor.

323. Extracting the lifting rods, in the plate system. After the plates of ice have been placed upon the tipping table, the ends of the lifting rods (which extend about halfway through the plate) are connected to the secondary terminals of a 1-kw. transformer, having a 220-volt primary and a 4-volt, 250-amp. secondary. In about 4 min. after the current has been turned on, the rods will be melted loose, and can be readily withdrawn.

324. Centre-freeze system. The can-system raw-water plant, frequently referred to as the "centre-freeze" or "core" system, undoubtedly presents the ideal of an electrically operated ice-making plant, as it has all the advantages of the can system, together with the productive economy obtained through the use of raw water. In brief, this type of plant consists of stationary cans, fed from the bottom, with raw water supplied through a cooling tank. During the period of freezing, the water in the cans is constantly agitated by a jet of air under a pressure of about 3 lb. per sq. in. The water freezes in the cans from the sides toward the centre, so that the space containing free water and all the impurities is gradually diminished. When this space has reached a very small area, all the water remaining, with the impurities contained therein, is drawn off, and the core is filled with distilled water; this, when frozen solid, gives a cake of very clean pure ice.

325. Auxiliary equipment of a 60-ton plant using the centre-freeze system. A 15-h.p. motor is belted to the line shaft, which in turn drives the following: 1 fan having a capacity of 500 cu. ft. per min., which is used for agitating the water in the freezing cans; 1 centrifugal pump having a capacity of 200 gal. per min., which is used in pumping the brine through the cooling or supply tank; 1 air compressor having a capacity of 40 cu. ft. per min., used to operate overhead cranes which are employed in removing the ice from the cans; 1 7.5-h.p. motor direct-connected to brine agitator. The distilled water used is furnished from a 10-h.p. boiler operated at from 10 to 15 lb. steam pressure.

326. Operating data on plant using centre-freeze system. The first complete month's operation of the above plant showed a total maximum demand of 125.8 kw., with an energy consumption of 91,056 kw-hr., and a production of 1,599 tons of ice. This is equivalent to a resultant maximum demand of 2.42 kw., or 3.24 h.p. per ton of ice, and 57 kw-hr. per ton of ice.

327. Domestic refrigerating equipments in their completed form, as placed on the market are in reality a self-contained refrigerating plant, especially adapted for use in homes, restaurants, butcher shops, clubs and apartment houses, or where the average requirements may run from 10 to 100 lb. of ice per hr., or the refrigeration effect equivalent to the melting of from 15 to 100 lb. of ice per hr. The universal method of drive is the electric motor which may be of any type, either belted, geared or direct connected, depending on the type and speed of the compressor used.

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These equipments are operated on the compression system using sulphur-dioxide (SO_2) as the refrigerant which condenses at a relatively low pressure. The complete equipment consists of a compressor, condenser, brine tank and automatic temperature control, the principal element being the compressor which is either of a reciprocating or rotary type; in the case of the latter it consists of a pair of herringbone gears running in oil which eliminates the use of suction and discharge valves and permits of a direct connected motor.

The temperature is regulated by a thermostat, located in the refrigerator food compartment, which controls the motor switch. It is customary to set the thermostat for about 45 deg. fahr. (7.2 deg. cent.) to be maintained in the food compartment, when the temperature rises above this, the motor switch is closed and the condenser set in operation, continuing to run until the temperature is reduced to that of the thermostat setting when the motor switch is opened.

328. Rating and operating characteristics of domestic refrigerating equipments, when operated under average conditions of brine at 27 deg. fahr. (−2.8 deg. cent.) and condensing water (at outlet) at 77 deg. fahr. (25 deg. cent.).

	Machine number			
	1	2	3	4
Capacity in B.t.u. absorbed per hr....	2,260	5,640	11,280	22,560
Capacity in pounds of ice per hr.....	10.5	26.0	52.0	105.0
Hours necessary to produce refrigeration equivalent to melting 100 lb. of ice.	6.38	2.55	1.28	0.64
Horse power required.....	0.55	1.26	2.15	4.3
Horse power of motor recommended..	0.75	1.50	3.0	5.0
Kw-hr. required to produce refrigeration equivalent to melting 100 lb. of ice.	2.63	2.39	2.09	1.57
Kw-hr. required to produce 100 lb. of ice.	3.92	3.62	3.15	2.34
Water at 68 deg. Fahr. (20 deg. Cent.) required, in gal. per hr.	40.0	100.0	200.0	400.0

To obtain actual power and energy consumption of motor, divide the above power values by the efficiency of the motor.

TEXTILE MILLS

BY WILLIAM W. CROSBY

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329. Mechanical drive from steam plant. If the power plant can be centrally located, the mechanical drive with a belt or rope tower, is most efficient. By this arrangement energy is imparted to the shafting on each floor directly. The steam plant usually proves the most flexible of the several methods of power development, and can often be placed at the centre of the mill; the proper location of the sidetrack and coal pocket must be considered.

330. Mechanical drive from a water-power plant is likely to prove inflexible. In a development of any size, the location and construction of foundations become difficult if the water wheels are at or near the centre of the plant. If they are located at one end of the mill, the shafting will be large, and the friction losses great. In some cases a canal may extend parallel with the river and the mills can be located between the canal and the river. Such construction allows several water wheels to be placed on the centre-line of the mill. While this last plan obviates the use of shafting of large diameters, it necessitates several control points, but this is not serious, for water wheels need but little attention after they have been started.

331. Steam auxiliary plant. There are not, however, many rivers whose minimum flow is sufficient to drive the mills dependent on them

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nd as textile mills, owing to their high capital costs, require a high rate of roduction, they should be provided with auxiliary steam plants capable of arrying the whole load, even though the water power has a good record for ependability.

332. Use of steam in textile processes. Nearly all textile mills must se steam at some point in the manufacturing process, and for heating the uildings in winter. A boiler plant is therefore essential and it generally ollows that one or more engines are employed to deliver their power to the ater-wheel shaft, the engine governor caring for the variations of load. In uch cases a portion of the steam power may be developed by simple engines perating against small back pressure, the exhaust instead of live steam eing used for certain processes; or steam may be taken from the receiver, if compound engine is used. If turbines are the prime movers, the bleeder ype may be used to furnish the necessary amount of low-pressure steam. n cotton mills the most common use for steam (aside from heating buildings) s in the slashers, which require a small amount steadily through the day. Woolen and worsted mills use steam for scouring, drying, back washing and combing. Finishing mills, which may form a part of either cotton or woolen mills, use steam for numerous purposes such as heating water, rolls, plates, etc.

333. Application of electric drive. Existing water wheels and steam engines can be made to drive generators, and even though the units are scattered, the control may be from a central point. In general the loads n textile mills are steady, and there should be close speed regulation. Electric drive is in general superior from the standpoint of speed regulation, aside from the advantages of flexibility and cleanliness.

334. Group and individual drives. In all kinds of textile mills anything that scatters dirt, lint, flecks, etc., becomes more of a nuisance as the goods produced become finer, for the finer textures reveal the foreign substance more plainly, and, being imperfect, are less valuable. In determining, therefore, whether to use individual drives or group drives, the presence of a belt becomes a deciding factor.

335. Type of motor adapted to textile mills. While for many reasons the direct-current motor meets the demands of the textile mill, the presence of more or less lint in the air makes the induction motor preferable. At the end of a day's run individual machines are disconnected from the drive, so that their motors will have but small starting loads; usually the totally enclosed squirrel-cage type is well adapted to the work. To eliminate a possible variation of speed dependent upon variable slip, a group arrangement may be employed where the constituent machines are either little affected by small changes in speed, or have constant loads. It is well to use only enclosed oil switches. Inasmuch as starting conditions are favorable there is often opportunity to use synchronous motors, if the power-factor is low, either on the same line-shaft with squirrel-cage motors, or in separate units.

336. Cotton-mill cards may be run in groups, belted from above or below.

337. Cotton-mill fly frames are driven from one end and may be so arranged that by means of extended shafts and two pulleys on each end of the motor, four frames may be driven by one motor. As these machines can be stopped individually, doffing and empty bobbin replacing may be accomplished without stopping more than one frame at a time. Ring spinning and twisting may well be treated similarly to fly frames, although here again individual motors may be used.

338. Looms are perhaps the most susceptible to power variations of any textile machinery. The power to drive a loom varies with the speed of the loom, usually expressed as so many picks per min., a pick being one strand of filling left in the warp by a traverse of the shuttle. While there are so-called positive shuttle looms, most shuttles are thrown across the lay of the loom by a blow of the picking stick. As the shuttle enters the box at the end of its traverse, it pushes out one side of the box, called the swell, which operates a stop motion; when the shuttle does not properly enter the box, the swell is not displaced and this is called "banging off." The speed of the shuttle must therefore be sufficient to accomplish this, yet not so much as to cause rebound. The adjustments vary with the speed. The power to drive a loom also varies with the weight of goods, the beat-up, the number of harnesses and boxes in use.

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339. Advantage of motor drive for looms. Overhead shafting and belts are objectionable on account of the damage likely to occur from flying slugs, oil, etc. As looms must be stopped and started continually, and as they start under full-load immediately, belts in weaving rooms require much attention if high efficiency is to be maintained. The shafting can be put below the floor, and long lines reduced by group drives, but the belt from shaft to loom remains. The individual motor obviates practically all of these troubles. It may be arranged to drive through a clutch or be geared directly to the loom. In the first case the motor is kept running all the time while in the second case it is started and stopped with the loom. The shipper handle of the loom is connected with the control switch of the motor, so that the operative has nothing new to learn. A direct-connected motor must start instantly with full-load torque. The induction motor with small slip has, then, an advantage over belted drives in cleanliness and in constant speed. **Variations in angular velocity** are undoubtedly less in the case of direct electric drives than with belted drives, as shown by tachometer readings.

340. Power requirements for cotton-mill machinery.

Gins saw	10 saws per 1 h.p.
Gins roller 40 in.	1.25 to 3 h.p.
Bale opener	2.0 to 3 h.p.
Hopper feeder	1.50 to 3 h.p.
Thread extractor	2.0 to 4 h.p.
Single cylinder beater	3.0 to 4 h.p.
Two cylinder beater	6.0 to 8 h.p.
Top flat card	0.20 to 0.33 h.p.
Revolving flat card, 40 in.	
Production per hr.	
7 lb	0.75 h.p.
9 lb	1.0 h.p.
12 lb	1.25 h.p.
Sliver lapper	1.0 h.p.
Ribbon lapper	1.0 h.p.
Comber, 6 heads	0.50 h.p.
Comber, 8 heads	0.75 h.p.
Railway head	0.33 h.p.
Drawing frame, 1 head	0.25 h.p.
Drawing frame, 5-head metal rolls	1.0 h.p.
Drawing frame, 6-head plain rolls	1.0 h.p.

Speeders,	Spindles per h.p.
Coarse	30
Intermediate	42
Fine	48
Slubber fly-frame; spindles per h.p.	50
Intermediate	60
Fine (roving)	90
Jack (fine)	110
Spinning-frame warp, 16's and coarser spindles per h.p.	70
22	75
40	85
60	95
80	105
Filling	
Spindles 8,500 rev. per min.	85
Spindles 9,700 rev. per min.	95
Twister sp. per h.p. 6,500 r.p.m.	80
Filling winder sp. h.p.	300
Spooler	200 to 300
Mule	100 to 120
Warper h.p.	0.25
Denn warper	1.00
Baller h.p.	0.50
Slasher (drum) h.p.	1.50
Plain loom narrow light	0.33
Fancy loom wide heavy	1.0
Reel 50 sp	1.0
Brush and shear	3.0
Folder	0.25

341. Automatic loom economies. It should be remarked that with the increase of automatic looms the necessity for frequent stopping and starting decreases. Automatic looms have increased production from, say 80 per cent. to 95 per cent., or even 98 per cent., but as yet they are not generally used except by plain-goods mills. However, their use in fancy-goods mills is increasing.

342. Woolen and worsted mill drives. Scouring bowls, which extend to considerable length, are satisfactorily driven by several overhead motors. These rooms are damp and the air is vapor laden. Pickers and cards may be driven in groups. Mules are usually set in pairs, and one motor may drive each pair. Combs, gill boxes and roving machinery, whether for Bradford or French systems, may be driven in groups. Cap, ring or flyer spinning frames may be arranged as for cotton ring frames, that is, four frames may be driven by one motor.

343. Manufacture of woolen and worsted yarns. Both woolen and worsted yarns are supposedly made of wool, but other fibres are often mixed

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ith the wool. In general, woolen yarn is made of short fibre and worsted long fiber. Furthermore, in woolen yarn the fibres are made to lie in a ariety of angles with reference to the axis of the yarn, for ultimately the bric is fulled or felted. The finisher card doffs narrow strips of the carded bre, passing them between rub rolls or aprons (or tape condenser), which, hile carrying the roping along, rub it into cylindrical shape. Forty or ore of these ends are wound on jack spools and are made into yarn by the ule. The tendency of the mule is to throw one end of each fibre to the out- de of the yarn, while holding the other end in the centre, that is, the shape f the fibre is helical.

With worsted, the fibre is combed after carding, to remove the short bres or noil. Then follow the processes of gilling and drawing, each of hich makes the fibres more and more parallel, just the reverse of the woolen rocess. The Bradford worsted system converts the roving into yarn by eans of the spinning frame, either cap, ring or flyer. The French worsted ystem starts with the "top," essentially the sliver, carded, combed and illed, wound into about 8-lb. balls. There is no twist in the sliver, and y the French process no twist is put in until the final or spinning process. n this case a mule is used which is much like the cotton mule, which keeps he fibres smooth and parallel.

344. Power requirements of woolen-mill machinery.

Cone duster, h.p.	7.0	Cards 48-in. h.p.	5 to 8.0
Wool and waste box duster h.p.	3 to 5.0	Back washer h.p.	3.0
Scouring bowls per bowl	3 to 5.0	Double baller gill box	2.0
Apron dryer	10.0	Weigh box	2.0
Stone dryer, 15 ft.	14.0	Noble comb	2.0
18 ft.	15.0	Intersecting gill box per head	1.0
21 ft.	17.0	Etirage, 10 porcupines	3.0
48-in. mixing picker	10.0	Reunion, 12 porcupines	3.0
48-in., 3-cyl. set cards to start	4.0	Chute, 24 porcupines	3.0
Running on light work	2.5	Bobinier intermediate, 40 porcupines	2.5
Heavy work	8.0	Avant finisseurs, 50 porc.	2.5
60-in., 3-cyl. set cards	10 to 15.0	Finisseurs	2.5
Mule 300 sp. 2-in. gage to start	5.0	French mule spindles per h.p.	50.0
Running	2.5	Cap and flyer spinning (Bradford system) spindles per h.p.	50
Large mules	7.5	Shoddy pickers	7½ to 10 h.p.

345. Power requirements of finishing machinery.

66-in. double shear	3.5	Raw stock dyeing machine, 1,000 lb. batch	3.0
Measuring, doubling and winding	0.75	Raw stock dyeing machine, 400 lb. batch	2.0
Two-cylinder gig	4.0	Hosiery dyeing, 200 lb., 400 lb.	1.0
80-in. 36-roll napper	7.5	Roll dyeing knit cloth, 4 strings	1.0
72-in. 20-roll napper	6.5	Roll dyeing knit cloth, 20 strings	3.5
Skein dyeing machine, 150 lb. batch	2.0		
Skein dyeing machine, 400 lb. batch	3.0		

PAPER AND PULP MILLS

BY JOSEPH H. WALLACE

Industrial Engineer, Member, American Society of Mechanical Engineers

346. General application. Motors are generally well adapted for driving pulp- and paper-making machinery where the source of power is steady and reliable and will insure continuous operation of the plant. The choice of the grouping method (group drive), or the assembling of several machines to be driven by one motor through shafting and belting, and the unit method (individual drive), or the driving of each machine by its individual motor, will be determined by local conditions of layout and the probability of one or more machines in a group requiring operation while others in that group are shut down. Where machines can be assembled in groups that are easily served by short lines of shafting, the grouping method is more often to be preferred. The motor units then become larger, and being fewer in number,

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installation and maintenance costs are reduced, and speed reductions are more easily secured without the use of countershafts or gears. The unit method is preferable in case of large machines or where direct-connected apparatus can be used, and in places where points of power demand are scattered and would involve long lines of shaft to group the machines together. It affords convenience in locating machines in places desirable from the operator's standpoint, and is preferable where individual control of machines is frequently required.

347. Equipment adaptable to motor drive. In the equipment of paper and pulp mills specially suited to motor-drive can be included the following: flat and centrifugal screens, stuff pumps, suction-box pumps, white water and effluent pumps, water-supply pumps, winders, rewinders, cutters, refining engines, elevators, exhaust fans, kollergangs, agitators, mixers, slushers, concentrators, savealls, wet machines, rotary digesters, rotary boilers, conveyors, shredders, chippers, supercalenders and beaters.

348. Jordan engines. The application of motors for driving Jordan engines is very successfully accomplished by direct connection. The motor is mounted on an extension of the Jordan base, and mechanical arrangements provided for the movement of the Jordan plug either by a coincident movement of the motor, or by a special form of coupling connecting the motor with the Jordan shaft. In the refinement of paper stock much depends upon the pressure put upon the Jordan plug as it rotates within its shell or casing. The power required is influenced by the pressure applied, and a good indication of what the refiner is doing is presented by the readings of a wattmeter placed in the feeder circuit to the motor. When power-factor correction is necessary or desirable, the direct-connected Jordan engine presents an excellent opportunity for attaching a synchronous motor large enough to provide for the required condensing effect. Jordan engines are started without the working load applied, and the friction load is usually within the capacity of self-starting synchronous motors.

349. Beaters. The question of driving beaters and other large units electrically will be largely affected by the elements entering into the generation of energy. Beaters are usually grouped, and driving can be economically accomplished through main line shafting. Considerable quantities of power are required within comparatively narrow limits, and conditions are often in favor of steam engine drive instead of motor drive, where the power can be developed in efficient slow-speed compound condensing steam engines located in close proximity to the beater room. This method is especially favorable where electric power is generated with steam-driven equipment. Mills deriving electric power from hydroelectric plants can usually adopt the motor drive for beaters with success.

350. Fourdrinier and cylinder paper machines that require variable speed, and steam for drying purposes, are driven best by variable-speed steam engines, using the exhaust steam for drying the paper. Pulp grinders are seldom driven by electric motors; the power requirements are so great that the method almost invariably accepted as the best is to attach the grinders direct to a water-wheel shaft.

351. Types of motor suitable. In general polyphase alternating current (induction) motors give the best satisfaction in pulp and paper mill service where constant speed is desired. In cases where variable speeds are required from the same motor, or where smooth and even acceleration is desired in starting, as in the operation of supercalenders, direct-current motors can be employed to advantage. In other cases the alternating-current motors will be lower in first cost, more reliable for continuous operation, and lower in cost of maintenance. It is possible to use motors of higher voltage with alternating current than with direct, resulting in a reduction in cost of transmission and distribution circuits. Induction motors wound for 2,200 volts are frequently used in units of 75 h.p. and over. For smaller size motors, 440 volts is usual and for lighting 110 volts is the generally accepted standard; 550 volts is quite as common and is considered more desirable than 440 by the author. Step-down transformers are convenient for lowering the voltage, and require a minimum amount of attention. Three-phase alternating-current has been found to be most adaptable to general uses in paper-mill work. With unity power-factor, the amount of copper required for distribution of energy will be about 25 per cent. less than that

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required by direct-current of equal voltage. The absence of commutators on induction motors is a decided advantage from an operating standpoint; and where slip-ring induction motors are provided with brush-lifting and short-circuiting devices, the element of fire hasard due to arcing disappears. A frequency of 60 cycles per sec. has been generally adopted as standard in the United States and Canada for paper- and pulp-mill practice, although 25 cycles is sometimes used where considerations outside the influence of the pulp- or paper-mill proper demand attention; 50 cycles is the accepted standard in Great Britain, and in some of the European countries.

353. Motor characteristics. Induction motors with short-circuited rotors of the squirrel-cage type can be well recommended for most applications to paper-mill machinery where the units require a small amount of power, ordinarily under 50 h.p., or in larger sizes when the motor can be started and brought up to full speed under a light load. The starting of large squirrel-cage motors draws heavily on the supply lines, and the selection of large units of this type of motor should be influenced by the size of the power-plant supplying energy to such motors. Unless the generating plant has large capacity compared with the size of the motor units to be started, the heavy draft of energy will lower the voltage sufficiently to affect other motors that may be in operation. In order to overcome the limitations of squirrel-cage motors in the larger sizes, motors of the wound-rotor or slip-ring type may be used. These are desirable when motors require starting under full-load, when the units are large, or when automatic or remote control of motors is necessary. Synchronous motors are desirable in cases where the required starting torque is low, for the beneficial effect that they have on the power-factor; when of larger capacity than the actual requirements for power, they can be used to raise a low power-factor. They are suitable for direct-connection to Jordan engines, and for motor-generators, but full consideration must be given to the available generator capacity supplying them, as their starting characteristics are similar to those of the squirrel-cage induction motors.

353. Switching equipment should be selected with great care, and motors should be provided with some form of automatic protection against overload. Fuses are often found to be unsatisfactory, and in large sizes are expensive for renewals. Oil-immersed switches fitted with overload and low-voltage release are much preferred for pulp- and paper-mill installations.

354. Specifications for motors to be used in pulp and paper mills should call for heavy-duty machines. Form windings are to be preferred and in squirrel-cage motors special attention should be given to the method of attaching the rotor bars to the short-circuiting rings. Moisture-proof insulation in windings is important. Motors should be rated for a temperature rise not exceeding 40 deg. Cent. (104 deg. Fahr.) for continuous operation and be capable of carrying 25 per cent. overload continuously without injurious heating.

355. Standardization of sizes, speeds and types is to be recommended when a considerable number of motors are required in the same mill. Standardisation will result in reduced number of repair parts and will often facilitate the interchange of motors in case of repairs.

356. Power required by paper- and pulp-mill machinery will vary through wide limits, oftentimes on the same machine. This is especially true in the case of beaters and Jordans, when a variety of product is made in the same mill. Loads will frequently vary 100 per cent. in the treatment of different stocks, and the most careful judgment is required in the selection of motors that will meet the maximum demand, as this condition may exist for much longer periods than the overload capacity of a motor for the average load would allow.

357. Power required by the constant line, operating in connection with a 104-in. Fourdrinier machine (Fig. 39). Power input was derived from wattmeter in feeder line to motor.

Kw. input	Amp. per phase	Volts	Power-factor	B.h.p. (motor efficieney, 90 per cent.)
65	99	440	0.87	78.4 h.p.

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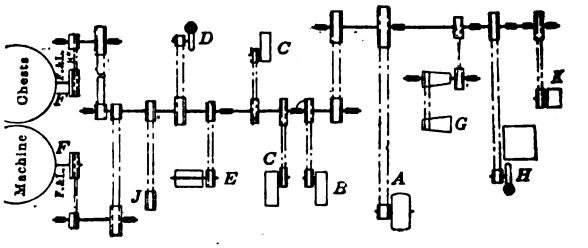


FIG. 39.

A—100-h.p. three-phase induction motor, 330 rev. per min.
B—16-in. by 18-in. vacuum (suction box) pump.
C—14-in. by 12-in. vacuum (suction box) pump.
D—8-in. fan pump (stock to screen).
E—10-in. by 10-in. triplex stuff pump.
F—Agitators in machine stuff chests.
G—Fourdrinier shake.
H—6-in. centrifugal for back water.
J—Three 12-plate screens.
K—Rotary vacuum pump for suction couch roll.

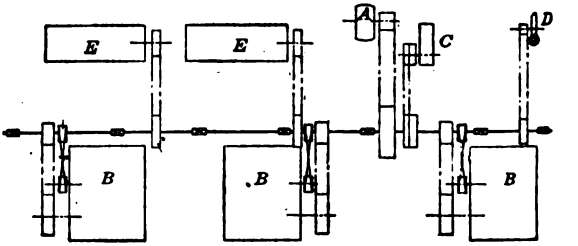


FIG. 40.

A—50-h.p. three-phase induction motor 570 rev. per min.
B—Three 72-in. wet machines.
C—14-in. by 12-in. vacuum pump.
D—Centrifugal pump.
E—Two 10-plate screens.

358. Test on group of wet machines (Fig. 40). Machines in operation—one wet machine, two screens, vacuum and centrifugal pumps and shafting. Power input derived from wattmeter readings in feeder line to motor.

Table of load variations

Kw. input	Amp. per phase	Volts	Power-factor	B.h.p. (motor efficiency, 90 per cent
18.0	43.0	440	0.55	21.7 h.p.
27.0	45.0	440	0.79	32.5 h.p.
29.0	46.5	440	0.82	35.0 h.p.
33.5	51.2	440	0.86	40.4 h.p.
36.0	53.8	440	0.88	43.4 h.p.

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359. Test on Jordan engine (Imperial size) direct-connected to 100-h.p. induction motor. Full-load speed 330 rev. per min.

Kw. input	Amp. per phase	Volts	Power-factor	B.h.p. (motor efficiency, 87 per cent.)
103.42	159.25	470	0.8	120.5 h.p.

Test was made on this machine for friction load, which showed an input of 10.6 kw. As the motor efficiency was low at this load, the friction load can be taken from 10 to 12 b.h.p.

360. Test on Jordan engine (Majestic size) direct-connected to 150-h.p. induction motor. Full-load speed 330 rev. per min.

Kw. input	Amp. per phase	Volts	Power-factor	B.h.p. (motor efficiency, 91 per cent.)
114.4	191	440	0.79	139.5 h.p.

A test on this motor at another time showed an input of 135 kw. or approximately 163 b.h.p. *The power consumed in Jordan engines will vary greatly in different mills and under various treatment of stock.* A test was made by the author on a Jordan engine of exactly the same size (Majestic) as that of the above test, which was direct-connected to a 200-h.p. induction motor, with the following results:

Full-load speed 350 rev. per. min.

Kw. input	Amp. per phase	Volts	Power-factor	B.h.p. (motor efficiency, 89 per cent.)
240	70	2,250	0.88	286.3 h.p.
235	68	2,260	0.88	280.4 h.p.
220	64	2,280	0.87	262.5 h.p.
200	60	2.240	0.86	238.6 h.p.
180	54	2,270	0.85	214.8 h.p.
*12	18	2,240	....	11.25 h.p.

361. Test on induction motor driving slitter and winder for 150-in. Fourdrinier paper machine. Friction load, 3 h.p.; winding load, 14.5 to 31 h.p.

362. Test on beaters, etc. Wattmeter observations made at a mill where four 1,500-lb. Horne beaters, agitator in stuff chest, and 10-in. × 12-in. triplex stuff pumps were driven through a short line of shafting from one motor, showed that 300 h.p. was required when beating strong sulphate pulp.

363. Summary of approximate power required by paper-making machinery

Constant speed line or pump line on paper machine	40–125 h.p.	Stuff pumps	5– 10 h.p.
		Chippers	75–100 h.p.
Fourdrinier paper machines (variable speed parts)	50–400 h.p.	Crushers	25 h.p.
		Barkers	10– 12 h.p.
		Grinders	250–350 h.p.
Beaters	30– 75 h.p.	Centrifugal screens	10– 15 h.p.
Jordan engines	50–300 h.p.	Supercalenders	50–100 h.p.
Screens, flat plate screens	4– 6 h.p.		
Wet machines	8– 12 h.p.		

* Test on friction load, engine running full speed with plug drawn out and no stock passing through.

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ELECTRIC DERRICKS AND EXCAVATING MACHINERY

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ELECTRIC DERRICKS

364. Derricks. Electric winches for derricks usually are driven by one motor for hoisting the load, hoisting the boom and for swinging. Sometimes the swinging is done by a separate motor.

365. Derrick motor sizes. For this service, electric motors are used running at 1,200 r.p.m. in the case of the small motors and as low as 450 r.p.m. in the case of the largest motors. Alternating-current motors are of the slip-ring induction type, the direct-current motors being either series or compound wound. The range of sizes is:

Derrick size, tons...	5	7½	10	15	20	25	30
Motor h.p.....	25	35	50	75	100	100	100

Drum-type controllers are used with the smaller and magnetic control with the larger motors. The size of motor to use is roughly found by obtaining the horse power required to raise the maximum load at the required speed and adding 25 per cent. to cover acceleration, friction, etc.

366. The hoisting speed of the load varies between 75 and 220 ft. per minute and usually between 110 and 150 ft. per minute.

367. Braking. When dynamic braking is desired, a compound-wound motor is used. Foot brakes are used in most cases. Where a motor is geared to the winch otherwise than by worm and worm gear, a solenoid brake should be used to prevent the load from getting out of control of the operator in case of failure of current.

EXCAVATING MACHINES

368. The principal types of excavating machinery are shovels and drag-line machines for work on land, and dipper dredges, clam shell dredges, hydraulic dredges and bucket-ladder dredges as floating excavating equipment. In addition to these are several other types for special work, but used in relatively small numbers.

369. The dragline excavator differs from the shovel in that the digging bucket is loaded by being dragged along the ground toward the machine with a rope wound on the drag drum. After loading, the bucket is lifted by a line on a second drum. The two drums are driven by one motor. The dragline has the same swing motion as the revolving shovel. This machine is used where a wide reach is desired, and where it is essential that the machine remain on top of the bank, digging below its own level, such as digging drainage ditches and building levees.

The operating cycle consists of digging followed by simultaneous hoisting and swinging followed by simultaneous swinging and lowering. The complete cycle is from 30 to 60 seconds, depending upon depth of digging and total angle of swing.

370. Motor sizes for dragline excavators. The same type of motor and control can be used to advantage on the dragline as on the shovel. The sizes of motors used are as follows:

(Bucyrus Co.)

Weight of machine in short tons	Size of bucket, cubic yards	H.p. of motors, intermittent rating		Transformers, (kv.a.)	Motor generator (set, k.w.)
		Drag and hoist	Swing		
35	1	50*	.....	45	40
55	1½	100	50	115	100
85	2	150	75	150	150
150	3½	200	100	225	175
200	4	250	125	300	200
300	5	400	200	450	350

* Continuous rating.

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ELECTRIC DREDGES

371. Hydraulic dredges. A typical dredge has a centrifugal pump with 20-in. diameter single suction and 20-in. discharge. The diameter of shell and runner is made to suit the maximum total head pumped against. The velocity in the pipe line is 12 ft. per sec. for easily transported material and as high as 16 and 18 ft. per sec. for heavy material containing flat stones. The percentage of solids pumped varies from 5 per cent. to 20 per cent., depending upon material and distance pumped. The pump is direct connected to a 750 to 1,000 h.p. variable-speed induction motor; synchronous speed 360 r.p.m., slow speed 270 r.p.m. The winch with five drums is driven by a 25 to 50 h.p., 600-r.p.m. variable-speed induction motor with 75 per cent. speed reduction. The cutter head driven by a 75 to 150 h.p., 600 r.p.m. variable-speed reversible motor. The motors are supplied with 2,200-volt, 3-phase, 60-cycle energy transformed from higher voltage on board the dredge.

372. Dipper dredges are very similar to shovels except that they have no thrusting action and the digging cycle is longer. Very few electrical types are in use. The motor and control equipment is similar to that used on shovels. The backing line to the dipper is operated by an independent motor or by the hoist motor. Provision is made for raising spuds and "pinning up" by power.

373. Clamshell dredges. There are very few electrically operated clamshell dredges. The stresses can be calculated exactly as they are limited to hoisting and swinging the loaded bucket. One type, has the swinging circle and hull equipped so that it can be pinned up on spuds, the other with wide enough hull to roll with the load, the hoisting line swinging the boom to one side and the bucket-opening line swinging the boom to the other side. The motor equipment and control are similar to those for shovels.

374. Bucket ladder dredges are used mostly for placer gold, tin and platinum mining. Electricity is the ideal drive. The energy consumed per cubic yard, excavated, washed and stacked varies from 1 to 1.75 kw.h. The usual equipment is 440-volt slip-ring induction motors. The digging motor is connected to the bucket drive by two belts and a jackshaft to take the digging shocks off the motor. All motors except pump motors are of the variable-speed type with secondary resistance for continuous operation from 50 per cent. to full speed.

375. Motor sizes for bucket ladder dredges

Bucket, cu. ft.	Average power demand, h.p.	Total rated h.p.	Bucket drive	Winch	Screen	Stacker	Main pump	Hopper	Miscellaneous
3	100	175	50	20	20	20	40	5	20
5	125	250	100	20	20	20	50	10	30
7½	300	365	150	25	30	25	75	10	50
9	450	515	200	30	30	50	100	30	75
16	600	845	400	35	75	60	150	50	75

ELECTRIC SHOVELS

376. Shovel motors may be of the enclosed type, the open type or the enclosed type with forced ventilation. The type to be used depends a great deal on the place of operation and the operating duty. Both alternating and direct-current motors are being used successfully for shovel operation. There is no one method or type of motor which adequately meets all conditions or is adaptable for all classes of service.

All of the larger electric shovels are operated by means of variable speed motors. These motors are usually of the mill type. This type of motor is selected also on account of its low armature inertia, permitting the armature to accelerate rapidly on small power. They are best suited to shovel work on account of their rugged bearings, cast-steel frames, and mica and asbestos insulation. The more rugged types of crane and hoist motors, which are

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Three systems are employed on the larger electric shovels, both railroad type and revolving type (Par. **381** to **383**).

381. Direct-current motors with rheostatic control. Direct-current motor equipment is used with rheostatic control, low-voltage direct current power being supplied to the shovel through flexible cables from an outside source. This method of operation is well adapted to meet conditions where the scope of operation is small and direct-current power is already available.

382. Direct-current motors with motor-generator set. Direct-current motor equipment is used, low-voltage power being supplied by motor-generator sets or synchronous converters located on the shovel, power being supplied through flexible cables from a two-phase or three-phase alternating current power system at 2,000 to 5,000 volts.

Where synchronous converters are used, control must be by rheostat only. By the use of motor-generator sets these conditions are removed and it is possible, by using a number of direct-current generators driven by one alternating-current motor, to use Ward Leonard or field control, thus eliminating rheostatic losses and securing several desirable operating characteristics.

The motor-generator set consists of an alternating-current moror driving one hoist, one swing and one thrust generator and one constant-voltage generator for exciting the other generators and the alternating-current driving motor if it should be a synchronous machine. The shunt fields of the generators are regulated to vary the speed and torque of the shovel-driving motors. No resistance is used in connection with the motors for reducing the voltage. Equipment of this kind may be operated at reduced capacity, even with very poor supply, with either rheostatic or field control. By the use of the field control system, it is practicable to operate a large shovel from a relatively small system without objectionable effect on the voltage regulation.

Where there is any doubt as to the capacity or the quality of power service, this should be investigated before purchasing electric shovels.

383. Alternating-current motors with rheostatic control. Two-phase or three-phase alternating-current motor equipment with rheostatic control is employed. Low-voltage alternating-current is supplied to the shovel through flexible cables from an outside source.

This method is suitable where the scope of operation is small and low-voltage current is already available. It is also suitable for contractor's work where the presence of high-voltage flexible cables might be objectionable. This same equipment may be used in connection with transformers mounted on the shovel, alternating-current power being supplied at 2,000 to 5,000 volts through flexible cables.

This is undoubtedly the best solution of the problem on large operations with an adequate power supply. The apparatus used is rugged and simple, being easily understood by the average operating man. It has the minimum number of rotating units and no commutators.

Another method is to use an alternating-current motor driving a single direct-current generator. Constant voltage is maintained at the generator and resistance is used in series with the hoist, the swing and the thrust motors. This machine is less efficient than the others because it has both motor-generator set and rheostatic losses. It has been given up largely in favor of the field-control machine.

384. Type of control. Regardless of which plan of electrification is used, the control is generally of the unit switch type except on very small shovels. These unit switches may be operated by compressed air or by solenoids. The air-operated control is the most compact, rugged type and occupies less space than the magnetic type. The unit switches are controlled by master controllers located conveniently for the operator. These may be arranged so that all operations are controlled by one operator or two operators, as desired.

385. Limitation of motor torque. A motor, being capable of sustaining large overloads, would cause an abnormally large amount of mechanical repairs on the shovel if its torque were not limited. The safe overload capacity of a motor large enough for the drive is beyond the overload capacity of the shovel consistent with good operation. This is due to the fact that for continuous operation of the shovel the continuous rating and not the overload rating, determines whether or not the motor is large enough.

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With rheostatic control, the motor torque is limited on the hoist, should the dipper strike harder material, by "jamming" relays which open the accelerating switches, thus inserting resistance in the circuit and holding the torque below predetermined maximum at any speed. In this manner, the shovel operator retains control of the motor, and its torque is not interrupted, nor is time lost, as would result if a circuit breaker were depended upon. Accelerating relays are used to limit the accelerating peaks of all motors.

With the direct-current field control shovel, where a separate generator supplies each shovel motion, the overload is limited by using a differential compound-wound field in the generator.

386. Special features. On the large electric machines, the dippers are dumped by small torque motors instead of by hand, as on steam shovels. With the exception of the smaller machines, the brakes for stopping and holding the various motions are air operated and automatically controlled. The smaller sizes of machines usually take the current aboard at less than 600 volts, and the larger sizes at the higher voltages, 2,300 and 4,000 volts. With the higher voltages, the ground cable is usually of the armored three-conductor type. Cable reels are sometimes used on the machines.

387. Regenerative control is used on some of the 300-ton shovels where the dipper dumps at a height of 60 ft. above the surface upon which the shovel stands.

388. Choice of equipment. The proper equipment to use will depend almost wholly upon local conditions. Motors are usually geared to shovel mechanisms in such manner that they will operate continuously over a given cycle without overheating. When geared in this way, the motors are usually operating at a very small percentage of their maximum torque usually under 50 per cent., due to their continuous rating. Either with the direct-current series motor or with the alternating-current phase-wound motor, a surplus of power is always available for exceptionally hard digging.

389. Reliability. Little consideration should be given to the relative efficiencies of the various kinds of electrical equipment for shovels; first, because the difference is small, and second, it is negligible when compared to the expenses due to delays inherent in shovel operation, such as waiting for cars and mechanical repairs. Reliability is the most important consideration.

390. Power supply. In most cases, the power source is alternating current, and the choice of electrical equipment will depend on the size of the generating station, power factor and peak loads, especially where purchased power is to be considered.

Where a large shovel is to operate from a small generating station, and where consideration in the rate schedule is given for high power factor or a penalty for poor power factor, the field-control shovel should be used with a synchronous motor driving the motor-generator set, since the load comes on gradually as compared to the resistance-controlled machine, thus permitting better voltage regulation for lighting customers. This is due to the fact that the input to the motor builds up from practically zero at standstill to full value with generator field control, whereas with resistance control the input is at full value immediately when the motor is connected to the line, even though the motor is initially at standstill and its power output nothing. The field-control equipment, being more expensive than resistance control, is for that reason limited to the larger machines which may cause more disturbance on the power lines.

BRICK MANUFACTURE

BY C. W. PENDELL

Engineer, Contract Dept., Public Service Company of Northern Illinois; Fellow, American Institute of Electrical Engineers

391. General arrangements. Brick-making plants vary considerably in their arrangements, depending largely upon the raw material used and whether raw material is quarried upon the property adjacent to the manufacturing plant or is delivered by railway from a distant point.

392. Raw materials. Various raw materials are used for various styles of bricks, as noted in Par. **393** to **396**. Brick-making clays, shales, etc., vary greatly in their natures and the individual raw material to be used should be carefully studied, analyzed and experimented with by an expert

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in ceramics to determine the proper working method of drying, temperature and duration of burning, etc., before the manufacturing plant is designed.

393. Common clay is used mainly for common building brick. It comes to the manufacturing plant in a semi-plastic condition and requires only to be thoroughly mixed, tempered (moistened when too dry; dried by the addition of dry clay, when too moist), and have all stones removed before being ready for the brick-making machine.

394. Shale is used for face brick and other high-grade building brick. It comes to the plant in a lumpy, dry, medium hard condition that at times requires crushing, always requires grinding, moistening and thorough mixing.

395. Refractory rocks used for bricks for furnace linings. Manufacturing plants are seldom located at the point where raw material is quarried. Rock is given a preliminary crushing at the quarry and is shipped to the manufacturing plant, where the first operation is crushing to the size desired by grinders. The method of grinding varies with the rock used and results desired; some rocks are ground dry and others are ground wet. These bricks are usually molded into shape on account of the abrasive nature of the material.

396. Silica sands used for bricks for furnace linings. They are given thorough drying and mixed with some sort of a binder, molded into shape and dried. The power demands are small in comparison to other classes of brick.

397. Stripping and digging. Brick plants using a common clay as a raw material are usually located adjacent to the pit from which clay is obtained. In such plants the digging and handling of the clay furnishes a problem all its own, being divided into "stripping" the "over-burden" or black dirt from off the top of the clay deposit, digging the clay and loading it upon cars, and hauling the cars to the foot of the incline leading to the manufacturing plant.

Stripping can be accomplished with the greatest ease and least cost by means of a "drag line" type of excavator (Par. **369**). Digging the clay requires a shovel type excavator (Par. **376**). Although both of these types of machines have failures charged to them in attempted electrification, both of them have been successfully motor-driven and there is no reason with present-day developments for not using motor-driven machines; the troubles of the past have been due mainly to lack of attention to details of control apparatus and ventilation of motors.

Both of these loads are severe on the source of power and the source must be able to stand the load fluctuations that will be imposed upon it. Both alternating-current and direct-current equipments have been built, one maker favoring one and another the other. The simplicity and ruggedness of the alternating-current equipment, however, is somewhat in its favor.

Motor-driven excavators and shovels are more economical than steam-driven machines on account of lessened amount of time out of service for repairs and the high cost of getting coal and water to steam machines. The water around such a plant is usually very hard and boiler repairs are frequent and costly on that account, as well as on account of excessive vibration of the machine. It will be found to be false economy to purchase too small excavators and shovels, with consequent poor results due to machines too small for the work.

398. Clay haulage. The haulage of clay cars from the shovel to the manufacturing plant is done in places by means of electric locomotives, both trolley and third rail types, but in small and moderate size plants a steam dinky locomotive usually works out to best advantage on account of the shifting of tracks as the cutting face changes, unevenness of ground, numerous spur tracks, etc. In larger size plants and in those where the clay pit is a half mile or more from the manufacturing plant, electric haulage works out advantageously. Local conditions must govern as to whether 250-volt direct-current trolley, 250-volt direct-current third rail, or 440-volt alternating-current three-phase trolley shall be used, considering carefully the hazard to workmen and mules, interference with digging shovels, initial cost, cost of shifting, location of tracks, frequency of track changes, maintenance, etc.

399. Pit drainage. The average clay pit has a water problem, which varies from getting rid of small amount of seepage water, to the emergency handling of flood water. This is a standard water-pumping problem in

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ant 2,200 volts. All parts of the plant will be within the radius of -volt distribution, except perhaps the drag line excavator used for stripping and the shovel used for digging clay.

403. Purchased power. If power is purchased from a central station, he voltage at which the central station company brings its wires to the brick lant has a great deal to do with the design of the distribution system about he brick plant.

If power is brought to the brick plant at a voltage higher than 6,600 volts, t should come to a single transformer station where it is reduced to the working voltage. If no excavators or shovels are used, a single bank of transformers reducing to 440 volts can be used. If large size excavators and shovels are used, it will often be of advantage to purchase untransformed current; install one bank of transformers for manufacturing plant and other power within 440-volt radius; install a second bank of transformers reducing to 2,200 volts, delta; extend an easily moved or semi-portable 2,200-volt line to portable banks of transformers on trucks adjacent to and pulled by the excavator and shovel; or if the excavator and shovel are operated by direct current with a 2,200-volt motor-generator set, the 2,200-volt line can be terminated on the excavator or shovel.

If the central station power is brought to the brick plant at 2,200 volts, 6,000 volts or 6,600 volts, it is sometimes of advantage to purchase untransformed current and extend a line at that voltage to various parts of the property, installing transformer banks adjacent to the main motor drive, fan house, pump house, excavator and shovel.

404. Private generating plant. Although, as stated above, 440 volts s the best motor voltage for a brick plant, the generating voltage of an electric plant installed to serve a brick plant will depend upon local conditions. If no electric excavator or shovel is used, 440-volt generation will probably be the most satisfactory. If, however, an electric excavator or shovel is used, or contemplated in the future, 2,200-volt generation, with a 2,200-volt line to the excavators and pump house, 2,200-volt main motor drive and a bank of transformers reducing to 440 volts for miscellaneous power, will be found most satisfactory.

405. Power requirements of individual machines. On account of the widely varying nature of the raw materials used, difference in methods required by different products, and great range in sizes of plants, it is possible to give only general figures for the horse-power requirements of the various units. A majority of brick plants, particularly those using common clay, are seasonal in their operation and cease operation when the ground freezes in the winter. If such a plant operates during winter months, consideration must be given to this fact and an additional allowance of from 10 to 20 per cent. in power requirements made to cover the handling of partially-frozen material.

406. Excavators and shovels. Motor capacities will range from 50 to 300 h.p., depending upon the size of bucket, length of boom and speed of operation. In some machines the motor or motors run continuously and the load is applied by means of friction clutches; in other machines the motors are started and stopped at each operation.

407. Haulage locomotives require from 15 to 80 h.p., depending on tonnage hauled, grades, curves in tracks, and speed.

408. Incline hoist. This requires from 20 to 75 h.p. Some saving in power can be made by using a "double skip" hoist, but this is a doubtful economy in a busy plant where a single hoisting track is not sufficient, owing to lack of flexibility.

409. Granulators and pug mills require from 15 to 150 h.p., depending on consistency of material, angle at which knives are set, speed of knives and amount of material handled.

410. Dry pan grinders. A 9-ft. pan is about standard and requires from 30 to 45 h.p., depending on material.

411. Rolls, smooth and grooved, require from 10 to 30 h.p., with momentary peaks of double the average amount as a stone is expelled. However, this depends upon how close the rolls are set together, the consistency of material and the amount handled.

412. Conveyors require from 3 to 15 h.p. Care should be taken that rollers supporting conveyor belts are placed close enough together so that

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the conveyor belt will not sag between rollers when loaded, as the power required to drive the belt increases very rapidly as the belt sags between rollers.

413. Auger machine. This requires from 40 to 250 h.p. depending on the work to be done.

414. Repress machines demand from 3 to 5 h.p.

415. Off-bearing belt. This will require from 7.5 to 15 h.p.

416. Transfer cars require from 7.5 to 10 h.p.

417. Fans consume from 15 to 50 h.p., depending upon the size.

418. Machine shop. The power demand varies from 5 to 10 h.p.

419. Oil pumps require from 5 to 15 h.p.

PRINTING, BINDING AND LINOTYPE MACHINERY

BY CHARLES E. CARPENTER

Engineer, Cutler-Hammer Manufacturing Co., Associate American Institute of Electrical Engineers

420. Control: Modern practice requires that most machinery of this class be equipped with self starters or self-starting speed regulators, operated from the line (service) switch or from one or more push-button stations. On account of the great number of bearings, gears, cams, etc., the load is largely frictional and the torque at starting is usually from 50 to 75 per cent in excess of the full-load running torque.

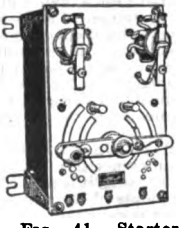


FIG. 41.—Starter-controller with self-contained line switch.

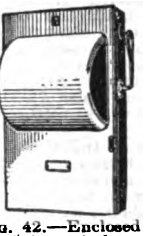


FIG. 42.—Enclosed service switch.

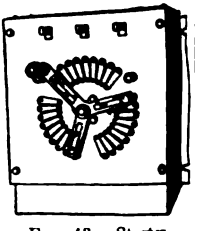


FIG. 43.—Starter-controller.

421. Job (platen) presses, with a heavy fly-wheel to accelerate, require speed regulation in the ratio of one to two from minimum to maximum. With direct current, about 40 per cent. speed reduction is obtained with resistance and about 20 per cent. increase by field control. With alternating current, 50 per cent. reduction is obtained by resistance. The controller (Fig. 41) is mounted on the wall and the enclosed service switch (Fig. 42) on the press.

422. Power required by job or platen presses

Size: inside chase	Maximum impressions per hr.	H.p.
8 in. × 12 in.	2,800	0.25
10 in. × 15 in.	2,500	0.25
12 in. × 18 in.	2,250	0.33
13 in. × 19 in.	2,100	0.33
14 in. × 20 in.	2,000	0.50
14½ in. × 22 in.	2,000	0.75
17 in. × 22 in.	1,700	1.00
Automatic feed, high speed		
13 in. × 19 in.	3,500	1.5

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423. Flat-bed (cylinder) presses require self-starting controllers equipped with predetermined speed setting, for push-button operation and wall mounting. With direct current, speed reduction of 50 per cent. is obtained with resistance and provision is made for 20 to 50 per cent. of shunt

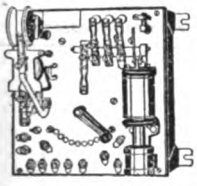


FIG. 44.

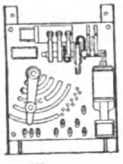


FIG. 45.

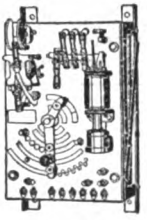


FIG. 46.

field variation; dynamic braking is also provided. If alternating current is used, 50 per cent. speed reduction is obtained with resistance, and if the press is equipped with automatic feed a solenoid brake should be used on the motor shaft for quick stopping. Accessories should be mounted directly on the machine. See the table in Par. **424**.

424. Power required by flat bed presses

Size of bed	Maximum impressions per hr.	H.p.
Single color—one cylinder		
26 in. × 34 in.	2,700	1.5
27 in. × 35 in.	2,600	2.0
28 in. × 41 in.	2,400	2.5
31 in. × 42 in.	2,400	2.5
32 in. × 44 in.	2,400	2.5
34 in. × 48 in.	2,300	3.0
35 in. × 50 in.	2,200	3.5
39 in. × 53 in.	2,200	4.0
43 in. × 56 in.	2,000	4.5
46 in. × 62 in.	1,700	5.0
46 in. × 68 in.	1,700	6.0
51 in. × 74 in.	1,600	7.5
Two color—two cylinder		
43 in. × 56 in.	1,700	9
46 in. × 62 in.	1,600	10
52 in. × 65 in.	1,500	12
52 in. × 67 in.	1,550	12.5

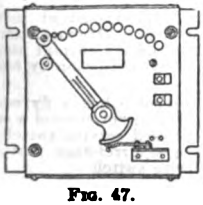


FIG. 47.

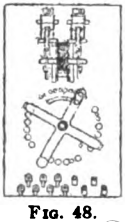


FIG. 48.

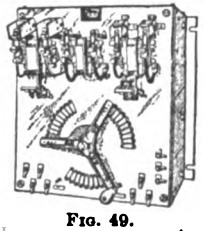


FIG. 49.

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425. Rotary lithographic presses require substantially the same equipment as flat-bed (cylinder) presses, except that they should have one more inching station for washing up and making ready, and the controller should be reversible to assist in taking off blankets and forms. Offset presses under this classification, where provided with Dexter automatic feeders, should have a feeder-clutch switch for automatically slowing down when the feeder clutch trips out.

426. Power required by rotary lithographic presses

Size of sheet	Normal impressions per hr.	H.p.
Zinc or aluminum		
32 in. × 45 in.	2,000	4
42 in. × 53 in.	1,800	5
45 in. × 65 in.	1,500	5
50 in. × 65 in.	1,400	5
Offset		
22 in. × 28 in.	4,000	2
26 in. × 34 in.	3,000	3
30 in. × 42 in.	2,800	4
34 in. × 46 in.	2,500	5
38 in. × 52 in.	2,400	6
44 in. × 64 in.	2,000	10

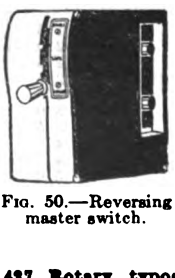


FIG. 50.—Reversing master switch.

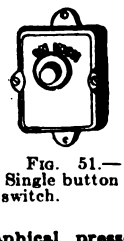


FIG. 51.—Single button switch.



FIG. 52.—Two button switch.

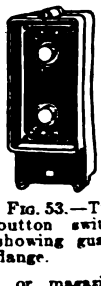


FIG. 53.—Two button switch showing guard flange.

427. Rotary typographical presses (not newspaper or magazine presses) require the same equipment as rotary lithographic presses, Par. 425.

428. Embossing presses require moderate-speed motors from 1 to 10 h.p. Direct-current motors should be compound wound with about 50 per cent. shunt field variation. Alternating-current motors should be of the slip-ring type with 50 per cent. speed reduction by resistance. Dynamic braking is not required.

429. Folders require motors of 0.5 to 3 h.p. Direct-current motors should have 50 per cent. speed reduction by resistance and 20 per cent. shunt field control; dynamic braking is not required. Alternating-current motors should be of the slip-ring type, with 50 per cent. speed reduction by resistance. No brake is required.

430. Paper cutters are started without load, except a heavy fly wheel, and require constant-speed motors of 1 to 5 h.p. For direct current a compound motor is required with self starter and enclosed service switch for starting and stopping. For alternating current a squirrel-cage motor is required, thrown directly on the line from the service switch.

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431. Motor and control requirements for printing machinery

Machine	Type of motor	Type of control	Accessories			
			If		Auxiliary stations	Line (service) switch control
			Reversing	Non-reversing		
Direct current						
Job (Platen) presses	Compound	Fig. 41				Fig. 42
Flat bed (cylinder) presses up to 3 h.p.	Compound	Fig. 45	Fig. 50	Fig. 52	One Fig. 51	
Same larger	Compound	Fig. 46	Fig. 50	Fig. 53	One Fig. 51	
Sheet feed rotaries, litho. or type up to 3 h.p.	Shunt	Fig. 45	Fig. 50	Fig. 52	Two Fig. 51	
Same larger	Shunt	Fig. 46	Fig. 50	Fig. 53	Two Fig. 51	
Embossing presses	Compound	Fig. 44		Fig. 52		
Folders to 1 h.p.	Shunt	Fig. 41				Fig. 42
Folders larger	Shunt	Fig. 45		Fig. 52	One Fig. 51	
Paper cutters, Guillotine type	Compound	Self starter				Fig. 2
Polyphase (*) Alternating Current						
Job (Platen) presses	Slip-ring	Fig. 43				Fig. 42
Flat bed (cylinder) presses up to 3 h.p.	Slip-ring	Fig. 48	Fig. 50	Fig. 52	One Fig. 51	
Same larger	Slip-ring	Fig. 49	Fig. 50	Fig. 53	One Fig. 51	
Sheet feed rotaries, litho. or type up to 3 h.p.	Slip-ring	Fig. 48	Fig. 50	Fig. 52	Two Fig. 51	
Same larger	Slip-ring	Fig. 49	Fig. 50	Fig. 53	Two Fig. 51	
Embossing presses	Slip-ring	Fig. 43				Fig. 42
Folders to 1 h.p.	Slip-ring	Fig. 43				Fig. 42
Same larger	Slip-ring	Fig. 48		Fig. 52	One Fig. 51	
Paper cutters, Guillotine type	Squirrel-cage					Fig. 42

(*) In case of single-phase motors up to 1 n.p., use Repulsion type self-starting variable-speed motors capable of 50 per cent. speed reduction below maximum. For speed regulator substitute Fig. 47 for Fig. 43. On job (Platen) presses variable-speed single-phase motors are frequently used with shifting brushes.

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432. Linotype and monotype machines require 0.25-h.p. motors started by throwing them direct on the line from the service switch. Linotype machines require back-geared motors of 400 r.p.m., with the machine drive shaft operating at 72 r.p.m. maximum. Monotype machines may have motors of 1,000 r.p.m., geared to machine drive shaft at 160 r.p.m. maximum. These machines on account of flying particles of type metal should be provided with fine gauze screening.

FLOUR MILLS

BY A. E. HALL

Manager, Milling Machinery Dept., Allis-Chalmers Manufacturing Co.

433. Drive. While a flour mill contains many separate machines, these machines must run as a unit, and it is not profitable from a commercial standpoint to drive each machine with a separate motor.

434. Machines included. A flour mill may be considered divisible as follows: (a) The roller mills or grinders; (b) bolting and purifying machinery, lofting elevators, conveyors and all the machinery in the mill proper above the roller floor; (c) the wheat cleaning department, and in the larger mills the wheat receiving machinery; (d) on navigable water, the marine leg. All the car pullers, passenger and freight elevators are operated from separate motors.

435. Power requirements of individual machines

Mill proper

	H.p. each	H.p. total
19 10×42 Style AA roller mills Corr.	17	324
20 10×36 Style AA roller mills smooth	20	400
12 80 in.×77 in. vibromotor universal bolters	3	36
20 8-ft.×32-in. centrifugal reels	4	80
4 8-ft.×32-in. round reels	3	12
22 7-ft.×30-in. purifiers	2.5	55
10 7-ft.×32-in. purifiers	2	20
5 aspirators for 7×40 purifiers	0.5	2.5
4 8-ft.×32-in. flour dressers	3	12
6 No. 7 bran and shorts dusters	8	48
2 70-in. double steel plate fan	27	54
2 55-in. steel plate fan	15	30
1 40-in. single steel plate fan	8.5	8.5
53 elevators	1	53
25 dust collectors	0.33	9
Total		1144

Wheat-cleaning department

	H.p. each	H.p. total
1 No. 4 comp shake Dbl receiving separator	8	8
2 No. 5 comp shake Dbl receiving separator	10	20
8 No. 90 milling separator	10	80
1 No. 7 automatic magnetic separator	0.125	0.125
1 No. 8 standard aut. magnetic separator	0.125	0.125
2 No. 10 standard aut. magnetic separator	0.375	0.75
1 No. 8 2 high scourers	40	40
2 No. 9 2 high scourers	50	100
1 No. 31 dust collec. for grinder	0.33	0.33
3 No. 32 dust collec. for grinder	0.33	1
4 No. 33 dust collec. for grinder	0.33	1.33
1 No. 36 dust collec. for grinder	0.33	0.33
4 No. 46 dust collec. for grinder	0.50	2
2 32-in.×8-ft. round reels with drums	3	6
1 30-in. attrition mill	60	60
1 45-in. double steel plate fan	14	14
16 conveyors		6
		340

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436. Types of motors. For the main driving motor in a flour mill, where as much as 700 h.p. is concentrated in a single motor, a wound-rotor slip-ring induction motor with a secondary resistance starter is recommended. The equipment should also include a primary panel containing an oil switch with overload and no-voltage trips, in order to protect the motor from excessive overloads or from failure of voltage on the supply line.

The smaller motors throughout the mill may be of the squirrel-cage type of induction motor, equipped with a potential starter or compensator.

437. Power requirements. The total power required to operate a mill having a capacity of 3,500 bbl. in 24 hr. will be approximately 0.4 h.p. per bbl. or 1,400 h.p. for the complete plant. This can be increased 10 per cent. in mills making only 100 bbl. or less per day. The power required for a flour mill varies considerably, depending on the condition of the wheat and the fineness of the flour to be produced, as damp or tough wheat or close milling require increased horse power. The hard varieties of spring wheat require more power than the soft varieties of winter wheat.

For an entire mill requiring 1,400 h.p., the wheat-cleaning department would consume one-fourth of this amount, or 350 h.p.; the roller mills one-half, or 700 h.p.; and the bolting machinery, which includes the sifters, purifiers, bran and shorts dusters, suction fans, elevators and conveyors, would require one-fourth, or 350 h.p.

BEET-SUGAR MILLS

BY WIRT S. SCOTT, M.E. IN E.E.,

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438. Power requirements. With electric motors properly applied, the total power consumption should not be over one-half of that required for steam-engine-driven factories. The machines of the types mentioned in Par. **439** to **456** inclusive, vary in size according to the individual requirements, but the examples cited will serve as a guide as to the average practice.

439. Beet lift. Sixteen feet diameter by 2 ft. wide, with 33 buckets 12 in. deep, making 4 rev. per min., driven by pinion meshing with 8 ft. gear on lift; 10 h.p. required, at constant speed, with high starting torque.

440. Beet washer. Six feet diameter by 18 ft. long, with thirty-two 24-in. arms or paddles. Shaft makes 14 rev. per min.; 7.5 h.p. required, at constant-speed and with a moderate starting torque.

441. Beet elevator. Thirty-four buckets, 22 in. wide by 17 in. deep, V-shaped; 70 to 120 ft. per min.; 10 to 20 h.p. required, at constant speed, with moderate starting torque.

442. Beet slicer. Capacity 50 tons per hr., 55 rev. per min.; 25 h.p. required, at constant speed, with high starting torque.

443. Cossette conveyor. Capacity 60 tons per hr., belt 12 in. wide by 125 ft. long; belt speed, 250 ft. per min.; 5 h.p. required, at constant speed, with light starting torque.

444. Sugar mixers. Shaft 50 ft. long, 12-in. paddles, speed 1.5 rev. per min.; 10 h.p. required, at constant speed, with moderate starting torque.

445. Tube mill or granulator; 6 ft. diameter by 30 ft. long, 10 rev. per min.; 10 h.p. required, at constant speed, with high starting torque.

446. Bagging machinery. Bag-sewing machine, requires 2 h.p.; bag stacker, requires 3 h.p.

447. Pumps. Hydraulic gasket pump, for operating doors on bottom of diffusion batteries, requires 5 h.p. Carbonation pump, 450 gal. per min., 50 lb. pressure, requires 25 h.p. Thick juice pumps, 450 gal. per min., 30 lb. pressure, requires 10 h.p.

448. Crystallizers. Ten feet diameter by 16 ft. long; paddles 4.5 ft. long secured to driving shaft which makes one revolution in 5 min. The power required varies considerably during the cycle of operation, the amount required at the completion of the operation being almost double that required at the start. For this reason the machines are best driven in groups of from four to eight, by one motor. For driving an individual machine,

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from 2.5 to 3 h.p. is required at the beginning of the cycle, and 5 h.p. at the end. Since the complete operation may require 60 hr., a motor must have sufficient capacity to operate at maximum capacity continuously with individual drive. Where crystallizers are driven in groups of from four to eight machines, 3 h.p. per crystallizer will be sufficient.

449. Centrifugals. The sugar centrifugal is one of the most important machines in sugar making, the operating conditions of which are very severe due to the inertia of the load and the cycle of operation. The time required for the complete spinning process varies with the grade of sugar. Ordinarily one man can operate two centrifugals on granulated sugar and up to four centrifugals on white sugar. When these machines are to be individually driven the cycle of operation must be known, as the rating of the motor will depend upon the root-mean-square value of the power requirements and the torque required for accelerating in a given time.

450. Average cycle of operation of group-driven centrifugals with fine granulated sugar. The average time required is as follows: filling one-fourth speed, 30 sec.; accelerating, one-fourth to full speed, 10 sec.; full speed, 120 sec.; power off, retarding by braking, 20 sec.; revolving at about 25 rev. per min., 30 sec.; total time, 3 min., 30 sec.

451. Average cycle of operations of individually driven centrifugals with fine granulated sugar. Filling basket, revolving by hand, 10 sec.; accelerating, 100 sec.; full speed, 30 sec.; power off, retarding by braking, 20 sec.; stop, unloading by hand, 60 sec.; total time, 3 min. 40 sec.

452. Average cycle of operations of individually driven centrifugals with coarse granulated sugar. Filling basket, revolving by hand, 10 sec.; accelerating, 60 sec.; power off, retarding by braking, 2 sec.; stop, unloading by hand, 60 sec.; total time, 2 min. 30 sec.

452(a). Average cycle of operations of individually driven centrifugals with coarse white sugar. Filling basket, 25 sec.; accelerating, 100 sec.; full speed, 15 min.; power off, braking, 30 sec.; stop, unloading by hand, 145 sec.; total time, 20 min.

453. Group-driven centrifugal machines furnish a very satisfactory arrangement, whereas individual drive, although successful, has been used to a much lesser extent. The character of the load is very similar to that of a fly-wheel, so that with these machines arranged in a group and driven by one motor, the centrifugals in operation will help to bring the idle machines up to speed and maintain a uniform load on the motor. This can best be shown by the following data. A group of ten 40-in. centrifugal machines, driven by a 100-h.p. motor, with 1 machine starting, requires 20.5 h.p.; with 2 machines starting, and 1 at full speed, 40 h.p.; with 3 machines starting, and 3 at full speed, 52.5 h.p.; with 4 machines starting, and 4 at full speed, 60 h.p.; with 1 machine at full speed 5.5 h.p.

454. When centrifugals are individually driven, the peak load is about eight times the normal running load; for a 40-in. machine the peak is approximately 40 kw. input, corresponding to about 40 h.p. output. Since at the very start the speed is zero, the horse power is zero, therefore the power required at start should be stated in terms of pounds torque at 1 ft. radius. The starting torque, together with the root-mean-square horse power for the cycle, furnishes sufficient data for determining the motor required.

455. The speed of a direct-connected centrifugal machine increases very rapidly at the start and at a much lower rate as the motor approaches synchronous speed. The motors are usually of the squirrel-cage type with high-resistance end rings designed to give approximately 15 per cent. slip at full-load; but, since full-load is never attained except at starting, the maximum speed which can be attained by the centrifugal is almost synchronous speed, and in nearly every case the operation is completed before the machine has attained its highest possible speed.

456. The torque necessary for starting a loaded centrifugal machine, and accelerating it to a given speed in a certain length of time can be determined by the following formula:

$$T = 2\frac{Wr^2}{g} \times \frac{2\pi N}{60 \times S} \qquad \text{(ft-lb.)} \qquad (8$$

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T = pounds torque at 1 ft. radius, W = weight in lb. to be accelerated, R = radius of gyration of entire mass in ft., N = rev. per min. machine will attain in S seconds, S = seconds required for accelerating.

The above expression does not take into consideration friction and windage, and it will be necessary to increase the result thus obtained by 10 per cent. in order to obtain the required starting torque.

LAUNDRY MACHINERY

BY FRITZ BALKER, M. E.

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457. Advantage of electric drive. The power laundry with its large number of different machines can employ electric drive to great advantage. The elimination of belts reduces the friction load of the plant, premits the convenient location of the different machines to reduce handling expenses, assures cleanliness and light, reduces danger of accidents and finally decreases the operating cost. From a number of tests all over the country this saving in operating cost appears to be from 25 to 30 per cent. Alternating-current polyphase induction motors are recommended wherever possible.

458. Use of steam in processes. When introducing electric drive in any laundry it must be kept in mind that a laundry requires a large amount of steam for drying and for the heating and boiling of water. This question is important in the controversy regarding the generation of electrical energy versus its purchase from a central station. In the latter event, steam must be produced independently of the source of power. In the majority of cases it will pay the laundry to have its own power plant, therby having the production of hot water as a by product of the generating plant. A careful study of conditions should be made, however, in order to determine which method is the most economical.

459. Classification. Laundries may be divided into three groups: (*a*) those doing family work only; (*b*) institution laundries (hotels and hospitals) (*c*) laundries doing railroad or steamship work only. Each of these groups has a different requirement for steam in amounts which can be expressed in terms of the horse-power requirements. Thus, for group (*a*) the number of pounds of steam used per hour could be expressed 1.2 times the horse power for that group; for group (*b*) 1.4 times the horse power; and for group (*c*) 1.8 times the horse power.

460. Method of drive. Group-drive of laundry machines is, generally speaking, not desirable, for the reason that the groups must contain machines which are not in constant use, and therefore the operating expense could not be reduced as satisfactorily. The table below gives the machine groups in their proper sequence for the three classes of work done in the laundry.

Flat-work group	Starched-work group	Rough-dry group
Washers	Washers	Washers
Extractors	Extractors	Extractors
Tumblers	Starchers	Dryroom-tumblers
Flat-work ironers	Dryrooms	
	Dampeners	
	Ironers and finishing machines	

All machines enumerated above should be placed on one motor, unless a laundry makes a specialty of one particular class, and does work in the other classes only a part of the time. In the latter case it is advisable to place all machines, which are frequently used, on one motor, and to group the others as outlined above. The load factor is between 40 and 45 per cent. Individual drive is recommended wherever possible, and the data in the following paragraphs refer to this class, unless otherwise stated.

461. Washers consist of a stationary outside shell, inside of which revolves a cylinder. The goods are placed therein and subjected to the action of the wash solution. To prevent tangling of the wash it is necessary that

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the cylinder alternate its direction of rotation. This reversing action is obtained in various ways, which are described in Pars. **463** to **465**. The load characteristic is different with each application and each case will therefore be treated separately. The cylinder should make from seven to twelve reversals per min., and in order to get the best results the surface speed of the cylinder should always be near 280 ft. per min. From a number of tests which have been made it appears that for every cubic foot of cylinder space the following power is required: 32 in., 0.04 h.p.; 36 in., 0.05 h.p.; 42 in., 0.06 h.p.

463. The power required by washers of standard size can be expressed as follows: 32 in. × 46 in., or smaller, 1.5 h.p.; 36 in. × 54 in., or smaller, 2 h.p., 36 in. × 70 in., or 42 in. × 54 in., or smaller, 3 h.p., 42 in. × 70 in., or smaller 5 h.p. These figures check quite well with the empirical data given in Par. **461**. The cylinders may have either of two kinds of perforations, the plain round embossed hole or the turbine slots; of these the latter require about 20 per cent. more power than the former, but are frequently used on account of the attendant saving in time and supplies.

463. Washers with belt reverse require either enclosed direct-current motors, having a 25 per cent. compound winding, or alternating-current polyphase motors with high-resistance rotors. The motors are mounted on a bracket on top of the washer, and the usual speed is 1,200 rev. per min. The use of a fly-wheel will add materially to the efficiency of the drive. The load factor is 65 per cent. A disadvantage arises through the necessity of using very short belts, with a consequent large loss of power. It is best practice to fully enclose the motors to prevent the entrance of steam or spray water.

464. Washers with reversing motors. Reversing motors applied to washers are probably the best for the purpose, but their success depends upon the method of control used. In these installations the motor is usually mounted on a bracket attached to the machine, for gear drive. On alternating current the use of wound rotor motors is recommended, and on the direct current the use of interpoles is imperative.

465. Timers for reversing washer motors. An auxiliary motor for timing is sometimes used to drive one or more controllers, which are constantly rotating and making the proper connections with the individual motors. Individual and mechanically operated timers are also used, the timer being actuated by the revolutions of the cylinder axle; or any other continually rotating part of the machine. The timer station operates a delay which in turn controls the reversing contactors. The load factor of this group varies between 55 and 60 per cent.

466. Extractors are machines employed to remove the water from the goods after washing. This is done by placing the pieces in a perforated basket and revolving the basket at a very high speed, whereupon the water is thrown out by centrifugal force.

467. Extractor speeds
(Troy Laundry Machinery Co., Ltd.)

Basket diameter (in.)	Speed (rev. per min.)		
	Copper	Steel	Monel metal
20	1,400	1,600	1,800
24	1,200	1,400	1,600
26	1,100	1,350	1,500
28	1,000	1,250	1,300
30	900	1,150	1,200
32	800	1,000	1,100
40	700	900	1,000
48	600	800	900

468. The power required to start an extractor is from two to three times the normal motor rating, but after the basket reaches its proper speed the power consumption drops very rapidly to only a fraction of the motor rating. The table below gives the necessary data for Troy machines with copper baskets, if run at the above speeds (Par. **467**). The power required to start the machine varies exactly as the square of the rated full speed.

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Basket diameter (in.)	Rating of motor horse power		Horse power running	Acceleration period (min.)
	Intermittent	At starting		
20	1.0	2.5	0.33	0.75
24	2.0	4.2	0.5	0.85
26	2.0	4.7	0.65	1.0
28	3.0	5.5	0.85	1.1
30	3.0	6.0	1.0	1.2
32	5.0	8.0	1.5	1.5
40	5.0	9.0	2.0	1.5
48	7.5	10.0	3.0	1.5

The above data were compiled from the results of a large number of tests; different loading, maintenance and speed conditions will, however, change these figures. The average load factor is 35 per cent.

469. Starchers are built for both collar and cuff work as well as shirt work. A great many types are on the market, the commonest machines being enumerated below. All direct-current motors should be enclosed on the pulley end to prevent the entrance of spray starch. For direct-current as well as for alternating-current they should be of the constant-speed, non-reversing type. The load factor is about 50 per cent.

(*a*) Collar and cuff starchers

American (Hagen type).	0.25 h.p.		
Troy No. 3	0.75 h.p.	Troy No. 6	0.25 h.p.
Troy dip wheel No. 1	0.5 h.p.	Troy dip wheel No. 2	0.5 h.p.

(*b*) Shirt starchers

Troy No. 1	0.25 h.p.	Troy No. 3	0.25 h.p.

470. Dryrooms. There are two types, one in which the goods are hung on racks, trucks, etc., and another in which the goods are carried through the room continuously on an endless chain conveyer. The first group requires a motor to drive a ceiling fan, for which purpose a 0.167-h.p. motor is used, with a load factor of 100 per cent. Conveyer dryrooms are built in various sizes and depths, the standard depth being 9 ft. Besides driving the chain, the motor operates one or more fans. The motor should never be mounted in the dryroom proper, as the temperature is very high. It is best practice to set the motor on a wall-bracket or to hang it on the ceiling and drive the regular countershaft of the cabinet by belt. The sizes are given by the number of loops (one-half the number of chains inside). Assuming, that the 2-loop room requires 1 h.p., it has been found by tests that each additional loop requires 0.5 h.p. Each additional fan requires 0.25 h.p., and for every foot added to the standard depth, additional power must be supplied mounting to one-sixth of the power required by a standard room of the same size. For example, the horse-power rating of a 4-loop conveyer dryroom 11 ft. deep, supplied with 2 fans may be calculated as follows: standard 4-loop room with one fan, 2 h.p., additional 2 ft. depth, 0.33 h.p.- additional fan, 0.25 h.p.; tota l, 2.58 h.p. The load factor of these machines is 65 per cent. The motors are of the constant speed, non-reversing type, and should be equipped with a rail base, for tightening the belt.

471. The dryroom tumbler is used for rough dry work. This machine consists of a revolving and reversing cylinder, enclosed in a suitable housing. One or more fans, usually directly attached to the machine, either blow or draw heated air over and through the goods to be dried. The motor is generally placed on the side of the machine, and drives a countershaft through a silent chain; the pulleys of the cylinder and fan shaft are driven from this countershaft. The machines are made in three sizes, 30 in. in diameter, which requires a 2 h.p. motor, 36 in. in diameter, requiring a 3 h.p. motor and 42 in. necessitating a 5 h.p. motor. The motor can be identical with drive described in Pars. **463** or **464** respectively. As far as the cylinder is concerned, the motor-driven fans, when the drive described in Par. **464** is employed, are directly coupled to the fan shaft. All direct-

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current motors should be compound-wound, with about 20 to 25 per cent. compounding. On alternating-current circuits plain squirrel-cage motors give good results. The load factor of motors driving tumblers is 60 per cent.

472. Dampeners are machines used to moisten all starched goods after drying and prior to the ironing process. A large number of machines are on the market, the table below (Par. **473**) giving some of the more prominent ones. No special features are required of the motors, and the load factor varies between 45 and 55 per cent.

473. Power requirements of dampeners

(*a*) Collar and cuff dampeners

Hagen..... 0.25 h.p. Troy No. 1. 0.3 h.p.	B. & E..... 0.75 h.p. Troy No. 2.. 0.75 h.p.	Wilson... 0.125 h.p.

(*b*) Shirt dampeners

B. & E... 0.375 h.p.	Bishop conveyor..... 0.5 h.p.	Troy.... 0.5 h.p.

474. Collar and cuff finishing machines. A number of machines comprise this class, of which only the ironers themselves are individually driven, while the small finishing machines are belted from a line shaft attached to the finishing table.

475. Collar and cuff ironers, for the most part, require no special motors However, in the case of steam-heated ironers, it may be sometimes desirable to use variable-speed motors, in order to choose the speed best adapted to the steam pressure, should the latter be changeable. The load factor is 55 per cent.

476. Power requirements of collar and cuff finishing machines

Troy No. 5.....	Gas-heated, 3 rolls, 24-in.....	1.0 h.p.
Troy No. 5.....	Gas-heated, 3 rolls, 40-in.....	1.5 h.p.
Troy No. 5.....	Gas-heated, 5 rolls, 24-in.....	1.75 h.p.
Troy No. 5.....	Gas-heated, 5 rolls, 40-in.....	2.0 h.p.
Troy No. 14.....	Gas-heated.....	1.0 h.p.
Troy.....	Steam-heated, all sizes.....	0.75 h.p.
B. & E. No. 22.....	Steam-heated.....	0.75 h.p.

477. Finishing table. The motor, which is of 0.5 h.p. capacity, is of the non-reversing constant-speed type, and geared directly to the line shaft, from which the small finishing machines are belted. The load factor does not exceed 45 per cent.

478. Shirt finishing machines. These machines are used to iron or press the neckband, bosom, sleeves and bodies of shirts. For each of these operations a special machine is used, in some cases there are several types of machine for each operation. See Par. **479 to 483.**

479. Bosom ironers. Three distinct types of bosom ironers are in use: first, the reciprocating type, where the bosom passes back and forth under a revolving drum; second, the one-way type, where the bosom travels in one direction only under one or more heated rolls; and third, the presses.

480. Reciprocating bosom ironers require a motor of 0.5 h.p. Reversals may be obtained by means of reversing switches, in which case direct-current motors must be compound-wound and alternating-current motors must have high-resistance rotors. Reversals may also be accomplished by means of mechanical-reverse devices, in which case non-reversing, constant-speed motors should be used. The reverse switch, as well as the mechanical device, is actuated by a foot treadle and lever connections. The load factor for reversing motors is 75 per cent., and for the mechanical reversing type 55 per cent.

481. One-way bosom machines require motors of 1 h.p. capacity, without any special features. The load factor is 55 per cent.

482. Bosom presses are built in two types. In one case a reversing motor operates a screw, and through it a toggle. This motor has a capacity of 0.5 h.p. Should it be a direct-current motor, it ought to be compound-

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wound; should it be an alternating-current motor, it ought to be equipped with a high-resistance rotor. Single-phase motors cannot be used unless some kind of mechanical reversing device is employed. The load factor is 75 per cent. The other type of press is operated by a fluid (usually oil) under pressure. A constant-speed, non-reversing motor of 0.5 h.p. capacity operates the pump. The load factor is 55 per cent.

483. Neckband ironers. For this service, small motors of from 0.125 to 0.25 h.p. capacity are required. There are no special features, and the load factor is 55 per cent.

484. Sleeve and body ironers. These machines are almost identical, their only difference being in respective size. All modern machines are reversing and, like bosom ironers, are reversed either electrically or mechanically. The sleeve ironers require a motor of 0.25 h.p. capacity; the body ironers, 0 5 h.p. If the reverse switch is used the motors must be built for reversing duty (compound-wound if for direct-current, or having high-resistance rotors if for alternating current). Single-phase motors cannot be used for this service. If the mechanical reversing device is employed, standard motors without special features should be used. The load factor of reversing motors is 75 per cent., of the others 55 per cent.

485. Flatwork ironers or mangles are used to dry and iron flatwork by passing the goods under pressure over heated rolls or chests. With rolls, one or more aprons may be used to insure perfect contact of the goods over the heated surfaces, and while not essential, this may also be done where chests are used. Nearly all machines of this class must be arranged to deliver goods at varying speeds, and the problem of motor selection must be carefully worked out in detail. The data given below represent the average results of a large number of tests.

486. Power requirements of flatwork ironers

(*a*) Flatwork ironers, chest-type without aprons	
Troy gas ironer	0.5 h.p., constant speed
Troy handkerchief ironer	0.5 h.p., constant speed
Troy addition 2, 3, 4 chest	0.75 h.p., armature control
Troy addition 5.6 chest	1.5 h.p., armature control
Troy triplex No. 1	1.0 h.p., armature and field control
Troy triplex No. 2	1.5 h.p., armature and field control
Troy triplex No. 3	2.0 h.p., armature and field control
Troy five roll (8-in. rolls)	1.0 h.p., armature control
Troy five roll (12-in. rolls)	2.0 h.p., armature or 3 to 1 field control
(*b*) Flatwork ironers, chest type with aprons	
Troy four roll	2 h.p., field control, 3 to 1 speed range
Troy six roll	3 h.p., field control, 4 to 1 speed range
Troy eight roll	7½ h.p., field control, 4 to 1 speed range
(*c*) Flatwork ironers, cylinder type	
Troy Trojan, 1 cylinder, 48 in.	2 h.p., field control, 3 to 1 speed range
Troy big two, 2 cylinder, 24 in.	2 h.p., mechanical regulation
Troy big two, 2 cylinder, 30 in.	4 h.p., field control, 3 to 1 regulation
Troy duplex, 1 cylinder, 24 in.	1 h.p., armature control
Troy addition, cylinder only 36 in.	1 h.p., armature control
(*d*) Flatwork ironers, chest and cylinder type (aprons)	
Troy addition, 1 cylinder, 36 in. and 2, 3, 4 chests	2 h.p., field control, 3 to 1 speed range

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487. Dry-cleaning plants. The underwriters do not allow the installation of electric motors in the cleaning room proper; therefore it is necessary to mount the same outside and operate the plant by group drive. The power required may be calculated from the above data for the various machines. The load factor, as in group drive, is 45 per cent.

SMALL MOTOR APPLICATIONS

BY BERNARD LESTER

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488. Small motor types and characteristics. There is a very broad use for small motors for the operation of appliances principally in the home, office, store, garage, and repair shop. Due to the extensive distribution of alternating current for illumination, single-phase motors are mostly used. Small motors may be classified as follows:

489. Single-phase types. The large majority of single-phase motors used in sizes of ½-h.p. and below are **split-phase induction motors,** which are simple in construction, reliable in operation, and possess speed-torque characteristics which are suited to the majority of driven machines. The principal limiting features in connection with the application of this type of motor are starting torque and pull-out (maximum) torque. Occasionally these motors are designed with an internal centrifugal clutch which provides an overload protection for the windings of the motor and tends to reduce the starting current and the length of time it is drawn from the circuit during the period of acceleration.

The **repulsion-induction motor** is now extensively used principally in sizes above ½-h.p. upon applications where the starting torque required is high and the lowest possible starting current is necessary. They are largely used for pumps, meat grinders, air compressors, etc.

490. Polyphase type. The squirrel-cage polyphase motor is preferable to the single-phase motor on account of its simplicity. Its use is largely limited to small motor applications in factories where polyphase current is available.

491. Direct-current types. Shunt, compound and series-wound direct-current motors are applied by following the same principles involved in the application of larger direct-current motors.

492. Universal types. The term "Universal" is applied to those motors which will operate either upon alternating current or direct current, either without any change whatever in adjustment of the brush rigging, or with the addition of external resistance, or with both of these features. Such motors are necessarily series wound and possess speed-torque characteristics in general similar to a series-wound direct-current motor. Consequently, their application, except in very small sizes, is limited to the driving of devices which are directly connected or geared to the motor. Obviously, applications must be such that a wide variation of speed with torque load is permissible. The application of universal motors is generally limited to certain types of fans and blowers, electric tools, and domestic sewing machines. The small portable vacuum cleaner which employs a blower is usually operated by this type of motor.

493. Service rating of motors. Obviously a motor which is required to operate under load for short intervals will not attain the temperature reached when operating at a similar load continuously. Consequently, for intermittent service, smaller motors may be employed than for continuous service. However, where the motor is frequently started and stopped, though the aggregate running time is small compared to the idle time, the heating may become excessive due to the frequent inrush of current incident to starting. The simplest method of arriving at the proper motor capacity is by actual trial of a sample motor, subjecting it to a cycle of operations which will be equivalent to the most severe service conditions.

494. Split-phase motor characteristics. In analyzing the speed-torque* characteristics and other features of split-phase motors for purposes

* Torque measured with brake-arm and scales at 1 ft. radius.

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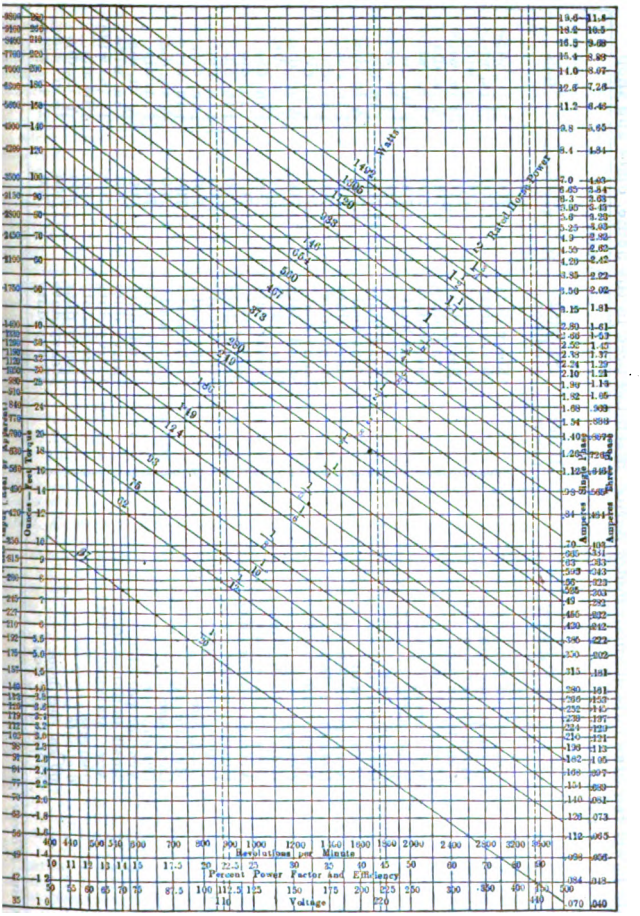


FIG. 54.—Characteristics of split-phase motors.

f application, Fig. 41, will prove of use in the calculation of approximate alue.

495. Calculation of full-load torque, knowing the horse power and the peed, may be illustrated by the following example: find the full-load torque f a 0.75 h.p. motor running at 1,700 rev. per min. at full-load (1,800 rev. per nin. synchronous speed). Find in Fig. 41 the intersection of the vertical line hrough 1,700 rev. per min. with the curve marked 0.75 h.p. (560 watts), and orisontally opposite this intersection at the left is the torque 36.5 ounce-feet.

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496. Approximate power requirements of small motor device machines used in the home, office and shop

Device		Motor			
Name	Capacity	Horse power	Starting condition	Rev. per min.	Belt
Air pumps	1 cu. ft. per min. air	¼	Heavy duty	1,700	½ in. wide
Air pumps, 130 lb. pressure	2½ cu. ft. per min.	½	Heavy duty	1,700	1½ in. wide
Air pumps, 130 lb. pressure	4½ cu. ft. per min. air	¾	Heavy duty	1,700	2 in. wide
Air pumps, 135 lb. pressure	6 cu. ft. per min. air	1	Heavy duty	1,700	2½ in. wide
Bread mixers	Household size	¼	Stand. duty	1,700	⅛ in. dia.
Candy mixers	Small sizes	½	Heavy duty	1,700	1½ in. wide
Centrifuges	Small sizes	1/10	Light load	1,700	¼ in. dia.
Coffee grinders	2 lb. per min.	¼	Heavy duty	1,700	1½ in. wide
Coffee grinders	Household size	⅛–⅙	Stand. duty	1,700	¼ in. dia.
Coffee roasters	25 lb. per min.	½	Light load	1,700	⅛ in. dia.
Duplicating machines	Average size for office	¼	Stand. duty	1,700	⅜ in. dia.
Egg beaters	Household size	⅛–¼	Stand. duty	1,700	¼ in. dia.
Envelope sealers	Average size for office	1/10	Light load	1,700	¼ in. dia.
*Ice cream freezers	2 quarts	¼	Stand. duty	1,700	⅛ in. dia.
Ironing machines	Rolls 7×26 in. long	½	Heavy duty	1,700	⅛ in. dia.
Ironing machines	Rolls 7×42 in. long	¾	Heavy duty	1,700	⅜ in. dia.
Mailing machines	Average size for office	1/10	Light load	1,700	¼ in. dia.
Meat grinders	Household size	⅛–¼	Stand. duty	1,700	¼ in. dia.
Revolving window table	Depends on display	½–¾	Stand. duty	1,700	¼ in. dia.
Sign flashers	Small size	1/10	Light load	1,700	¼ in. dia.
Sign flashers	Medium size	½	Light load	1,700	¼ in. dia.
Sign flashers	Large size	¾ and up	Light load	1,700	⅛ in. dia.
Small water pumps	120 gal. per hour	¼	Heavy duty	1,700	⅜ in. dia.
Vacuum cleaners	Average portable	¾	Stand. duty	1,700	⅛ in. dia.
Vacuum cleaners	Small stationary 600 r.p.m.	¼	Heavy duty	1,700	1 in. wide
Vacuum cleaners	Aver. stationary 600 r.p.m.	½ and up	Heavy duty	1,700	1½ in. wide
†Washing machines	9 sheets	¾	Heavy duty	1,700	⅜ in. dia.
†Washing machines	6 sheets	½	Heavy duty	1,700	⅛ in. dia.
Water pumps	60 gal. per hour	¾	Heavy duty	1,700	1½ in. wide
Water pumps	720 gal. per hour	1	Heavy duty	1,700	2½ in. wide

* Speed of freezer about 175 rev. per min.

† Includes wringer.

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497. Starting torque. Since the starting torque and the pull-out or maximum torque of a small split-phase induction motor are limiting features, care should be taken that the motor selected will start the driven machine under the severest conditions of torque. The starting torque varies approximately as the square of the applied voltage, and any reduction in voltage caused by the inrush of current incident to starting, and possibly emphasized by insufficient wiring or transformer capacity in commercial circuits, reduces very materially the starting torque delivered by the motor. It is customary to select a motor which will start the driven machine at a voltage of approximately 80 per cent. of the normal circuit voltage.

The starting torque and the maximum running torque can be found by multiplying the full-load torque by the proper constants. For example, if the starting torque of the particular motor considered in Par. **495** is 1.5 times the full-load torque, its value will be $1.5 \times 36.5 = 55$ oz-ft. Likewise if the maximum running torque of the motor is 2.5 times the full-load torque, its value will be $2.5 \times 36.5 = 91$ oz-ft. These constants must be determined from the characteristic curves of the individual motor, Fig. 41.

498. The horse power at maximum torque can also be determined from the curve if the speed is known. For approximate results the slip of small split-phase induction motors at maximum torque can be assumed to be 3 per cent. In the case of the motor discussed in Par. **496**, the speed at maximum torque will therefore be approximately 1,350 rev. per min. Find in Fig. 41 the intersection of the vertical line through 1,350 rev. per min. with the horizontal line through 91 oz-ft. torque; this is near the line representing 1.5 h.p., which is the approximate power developed by the motor just before pulling out, or stalling.

499. Input. The problem is to find input in watts, when given the horse power and the efficiency. Assume for example that the efficiency of a 0.75-h.p. motor is 75 per cent. Find in Fig. 41 the intersection of the vertical line through 75 with the 0.75 h.p. curve, and horizontally across from this intersection is the value 746 watts.

500. Current per phase. Knowing the watts input, the power-factor and the voltage, the problem is to find the current per phase (or per terminal); for example, assume that the power-factor of the foregoing motor is 70 per cent. and the voltage is 220 volts. Locate in Fig. 41 the intersection of the 70 per cent. vertical power-factor line with the diagonal representing 746 watts. The horizontal line passing approximately through this point, represents 1,050 apparent watts. Then from the intersection of the vertical line representing 220 volts with the diagonal representing 1,050 watts, the horizontal line representing amperes may be determined, namely, 4.8 amp. single-phase, or 2.8 amp. three-phase. The current per terminal in a two-phase motor is one-half that for a single-phase motor, and in this case would be 2.4 amp.

501. References to literature on small motor applications. There is practically no information available upon small motor applications. Reference may profitably be made to the following articles by the writer.

"Small Motor Applications," *Electric Journal*, February, 1911; Vol. VIII, No. 2.

Note on the "Application of Small Induction Motors," *Electric Journal*, November, 1912; Vol. IX, No. 11.

LESTER, BERNARD.—"Fractional Horse-Power Motor," Load, *Proc.*, A. I. E., Vol. XXXIV, page 385.

LESTER, BERNARD.—"Electric Drive in Domestic Engineering," *Electric Journal*, Feb., 1917.

DELLENBAUGH, F. S., JR.—"Split-Phase Motor Starting Switches," *Electric Journal*, May, 1917.

WEBER, C. A. M.—"Winding Small Single-Phase Motors," *Electric Journal*, May, 1917.

BEELER, V. M.—"Domestic Engineering," *Electric Journal*, June, 1917.

SMITH, H. B.—"Motor Drive in the Preparation of Food," *Electric Journal*, Jan., 1918.

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MOTOR CONTROL

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STARTERS

502. Necessity for starters. Standard direct-current motors of small capacity and of any winding may be thrown directly on the line without requiring an undue rush of current and without being injured. Specially designed motors as large as 10 h. p. can be started in the same manner, but larger machines—whether shunt wound, compound wound, or series wound—require some form of starting device not only for restricting the current inrush at starting but also for the protection of the motors themselves. Also see Sec. 5.

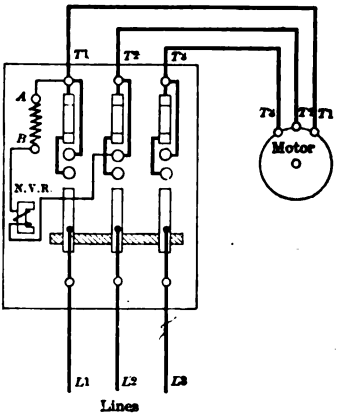


FIG. 55.—Starter for alternating current polyphase motor.

Standard alternating-current squirrel-cage motors of moderate potential and of any capacity may be thrown directly on the line without injury. High-voltage motors are made only in large capacities, and it is inadvisable to throw such motors directly on the line because of the line surges which are the invariable result of such procedure.* Even in the case of machines of moderate potential the current inrush is so great as to cause serious line disturbances if any except small machines are started in this manner, and most power companies prohibit this practice with motors of capacity exceeding 5 h.p. Fig. 55 shows a polyphase motor starter, with fuses which are out out during starting. Generally speaking, the starting current required by standard squirrel-cage motors when thrown directly on the line is from five to eight times that required under full-load conditions.

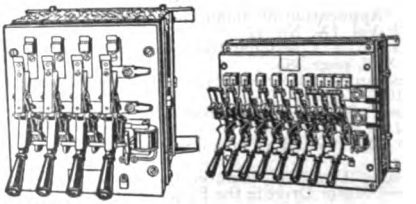


FIG. 56.—Direct-current starter for large motors.

503. Direct-current starters in their simplest form consist of a resistance of such value that only a proper current inrush is allowed, together

* Par. 541, No. 20.

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with a switching device for removing this resistance in one or more steps. In small and moderate capacities the switching device generally employed for short-circuiting the starting resistance, consists of a lever movable across a series of contacts which are connected to the starting resistance.

The **no-voltage release** which is usually a part of the direct-current starter consists of the resistance-controlling lever normally held at the extreme left or in the open-circuit position by means of a spring, and an electromagnet in series with the shunt field of the motor, adapted to hold the starting lever in the full-speed position as long as there is voltage on the line. In case of voltage failure this magnet will be de-energized, and the starting lever will return to its open-circuit position. This no-voltage release magnet is sometimes placed in the shunt-field circuit, and is sometimes connected across the line. The former arrangement is preferable because the motor circuit will be opened in case of failure of the shunt-field circuit.

In large capacities the use of a series of successively closed manually operated switches seems to be preferred by most controller manufacturers. Interlocks are usually provided which prevent the closure of such starting switches in any other than their regular order. Fig. 56 shows typical starters of this class.

504. Apportionment of resistance in direct-current starters. Fig. 57 shows the starting current required by a direct-current motor, it being assumed that a step of resistance is cut out each time the current falls to a predetermined value. For equal starting peaks the resistance must be divided unequally, the proper ratio between successive steps being a geometrical progression. The resistances of the steps, as well as the current peaks which will obtain, may be determined graphically from Fig. 57, where I_1 = initial inrush; I_2 = current at which a step of starting resistance is removed; I_3 = running current; r_0 = resistance of motor and its connections; R = external starting resistance. The ratios of progression with various numbers of starting steps, n, and for various values of α (which equals r_0/R) are given in the following tabulation:

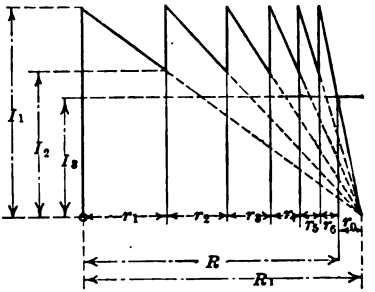


FIG. 57.—Direct-current motor starting current.

I_1 = Current peak.
I_2 = Current just before a step of resistance is cut out.
I_3 = Running current.
R_1 = Total resistance.
R = External or starting resistance.
r_0 = Resistance of motor and its connections.
$r_1, r_2, \ldots, r_n$ = Resistance of starting steps.

n	Values of α					
	0.03	0.04	0.05	0.06	0.08	0.10
2	5.97	5.02	4.47	4.09	3.54	3.16
3	3.22	2.92	2.71	2.56	2.32	2.16
4	2.40	2.23	2.11	2.02	1.88	1.78
5	2.02	1.91	1.82	1.76	1.65	1.59
6	1.79	1.71	1.65	1.60	1.53	1.47
7	1.61	1.58	1.54	1.49	1.44	1.39
8	1.55	1.49	1.45	1.42	1.37	1.33
9	1.48	1.43	1.39	1.37	1.32	1.26
10	1.42	1.38	1.35	1.32	1.29	1.25

* Par. 541, No. 27.

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The above takes no account of motor impedance or armature acceleration and, for this reason, practical results may be quite different from those calculated. The current-carrying capacities of starter resistances are proportioned for short-time duty; this determination of carrying capacity is more a matter of experience than calculation.

505. Star-delta switches for starting alternating-current motors, are used in connection with specially designed, three-phase, squirrel-cage motors whose windings are adapted for connection in star during acceleration and in delta for running. This form of starter is not often used in capacities exceeding 25 h.p. nor with potentials exceeding 550 volts. Fig. 58 shows the connections for this form of starter. Although not shown by the diagram (Fig. 58), star-delta switches are almost invariably arranged either to short-circuit the fuses entirely during starting or to transfer starting current through a second set of fuses which are of higher capacity than the running fuses. Some arrangement of this sort is almost essential, for if the starting current passes through the running fuses, they must be made so large as to afford practically no protection against overloads in normal operation. Star-delta switches are often equipped with no-voltage release, the magnet in such instances being connected directly across the line.

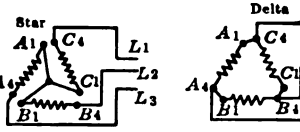


FIG. 58.—Connections of delta-star starter.

506. Time-limit overload protection. A better protection is afforded by time-limit overloads, which permit the starting current to flow for a limited time and which when the overload continues de-energize the low-voltage release and thereby disconnect the motor. A typical application of these overloads is shown in Fig. 59.

507. Primary-resistance alternating-current starters are employed to a limited extent in connection with two-phase and three-phase squirrel-cage motors, and, to a considerable extent, in connection with single-phase motors which start as repulsion machines. They are of the same general form as those employed with direct-current motors, except, of course, that where they are used in connection with two-phase or three-phase motors, they must provide for the inclusion and removal of resistance from two lines instead of one. Since polyphase motors require greater starting currents when started by the primary-resistance method than when induction starters are employed, primary resistance is not often resorted to in any except the small capacities. Its one advantage over the induction type of starter lies in its lower first cost and its greater simplicity. The single-phase starters are often equipped with no-voltage release, the no-voltage coil being connected across the line. Polyphase resistance starters are usually of the drum-controller type with one or two steps of resistance per motor phase.

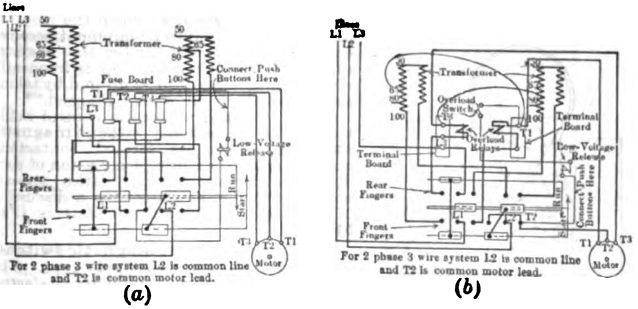
508. Induction starters for alternating-current motors are more widely employed than any other form of alternating-current starting device. They consist of an auto-transformer together with a switching device for connecting the stator winding, first across reduced potential obtained from the starting transformer, then directly to the line. In large capacities these induction starters are often arranged to operate in three or more steps, thus reducing the current surges. For moderate-capacity machines they are generally designed to connect the stator first across transformer taps which deliver from 50 per cent. to 80 per cent. of line potential, and then to the line. Induction starters are almost invariably arranged to disconnect the starting-transformer windings from the line in all positions except the starting position.

Induction starters are also arranged to short-circuit the individual running fuses during starting. Sometimes the starting current is taken through auxiliary starting fuses of heavy capacity, but in most instances the motors are unprotected during starting. This class of starter is now almost invariably equipped with no-voltage release, and often with overload release which replaces the fuses. The overload release generally takes the form of overload relays which are adapted to open the circuit containing the no-voltage release magnet; this allows the switching mechanism to open the motor

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circuit. Where overload release is employed, the overload relays are individually short-circuited during starting. Fig. 59*a* is a connection diagram for a typical induction starter with no-voltage release and protected with fuses, while Fig. 59*b* shows the same device supplied with overload release.

In large plants one bank of starting transformers is sometimes employed for starting all motors, and a five-wire system is installed. Where this arrangement is employed the motors are first connected to a common line



and two starting lines, and then directly to the distributing mains. Fig. 60 shows the arrangement described.

509. Secondary-resistance starters for alternating-current motors are used in connection with alternating-current slip-ring motors for the purpose of increasing the secondary impedance during starting, and are of the same general type as primary-resistance starters. Since slip-ring motors almost invariably have their secondaries wound polyphase, it is quite important that the starters used with such motors be designed to keep the secondary circuit as nearly in electrical balance as possible, for any unbalancing of this circuit reduces the starting torque which it is possible to obtain with a given line current.

Secondary-resistance starters are sometimes entirely separate from the switching apparatus used to open and close the primary circuit. In other instances the primary switch is interlocked with the device for controlling the secondary resistance in such a manner as to prevent the closure of the former unless the latter is in a position where all secondary resistance is in circuit. Where a slip-ring motor is started and stopped at frequent intervals, the primary switch and the secondary resistance commutating device are often connected to a single control lever, so that, as the latter is moved from the "off" position toward the full-speed position, the primary circuit is first closed and then the secondary resistance is removed step by step.

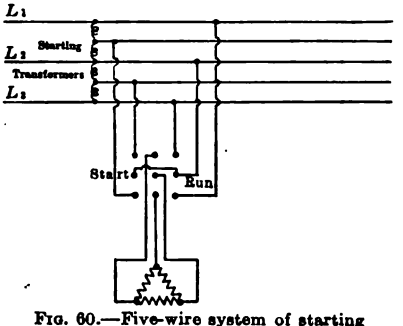


FIG. 60.—Five-wire system of starting alternating-current motors.

The characteristics of motors with which secondary-resistance starters are employed have so much influence upon the design of the resistance th-

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it is impossible to lay down any rules governing the determination of the ohmic value of the various steps; see Sec. 7. Non-inductive resistances should be used exclusively in the secondary circuit of slip-ring motors.

510. Automatic or self-starters are used in connection with both alternating-current and direct-current motors when it is desired to have them start and stop automatically in response to variations in pressure, water level, etc.; or when it is desired to start the motor with greater convenience and with less demand upon the intelligence of the operator than is required where hand-operated starting apparatus is installed; or when the motor is so large that its control equipment becomes cumbersome and difficult for the operator to handle; or when the motor is frequently reversed and is likely to be injured by taking an excessive current when "plugged."*

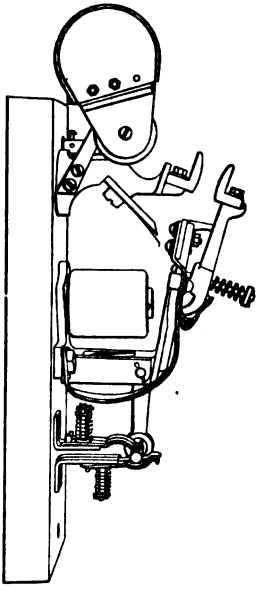


FIG. 61.—Direct-current magnetic switch.

Self-starters and automatic control would be an utter impossibility without **magnetic switches** (sometimes termed contactors) and consequently a brief description of such devices and their characteristics appears necessary before entering into a discussion of the various types of self starters (Par. 511 to 518).

511. Direct-current magnetic switches are generally of the single-pole type. The most common form is operated by an electromagnet of the clapper form (Fig. 61). The movable element or clapper carries a contact member adapted to engage a corresponding stationary contact, and a flexible connection carries current to the contact mounted on this moving clapper. Because an electromagnet adapted to long-pull work is inherently inefficient and slow in operation, the modern contactor is almost invariably arranged for a short break and in large capacities must be provided with a magnetic blow-out for disrupting the arc. In small capacities the arcing contacts are often used for carrying the current as well, but in larger capacities the main or current-carrying contacts generally consist of laminated brushes which engage contact plates. This laminated contact is protected against arcing and burning, by auxiliary contacts located in the magnetic blow-out field; these are adapted to engage sooner than the laminated contacts, and to open later. Fig. 61 shows a typical direct-current contactor with the blow-out pole pieces swung upward so as to render the contacts easily accessible for repairs.

In order to be quick acting and positive in operation, direct-current contactors should have coils which are capable of closing the switch with potential equal to 75 per cent. of normal impressed at the coil terminals, when the coils are at the operating temperature.

512. Alternating-current contactors are almost invariably called upon to handle two circuits simultaneously and are, therefore, almost invariably of the double-pole type. They are generally of the clapper form, but the magnetic circuit is necessarily laminated. Particular care should be taken to insure the holding of the laminations with sufficient rigidity to secure a permanent structure. The pull exerted by an alternating-current magnet is proportional to the square of the voltage impressed at its terminals, consequently it is not practicable to make alternating-current contactors which have the same operating range as direct-current contactors.

* Par. 541, No. 8, 9, 13, 25.

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It is practically impossible to obtain sufficient sealing pressure with alternating-current magnets to allow the use of laminated contacts, and, as a result, most alternating-current contactors depend upon butt contacts of copper for opening the circuit and for carrying the current when closed. Alternating-current contactors designed for voltages up to 550, are almost invariably equipped with magnetic blow-outs, and those built for higher potentials are generally arranged to open the circuit under oil. Air-break contactors have been made, however, for potentials up to 2,200 volts. These high-potential contactors are equipped with horn-type arc gaps, which permit the arc to increase in length until it reaches the point of disruption.

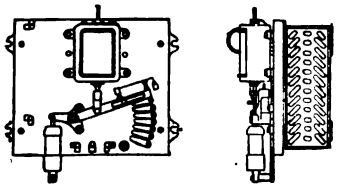


FIG. 62.—Direct-current time-acceleration starter.

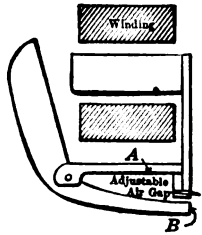


FIG. 63.—Series switch-operating magnet.

513. **Time-acceleration self-starters** are designed to accomplish the necessary starting operations in a pre-determined and adjustable period. The timing may be accomplished in many ways, but a solenoid whose action is retarded by an adjustable dash-pot, is perhaps the most widely used device. A typical direct-current time-acceleration starter is shown diagrammatically in Fig. 62.

514. **Current-limit self-starters** are devised to halt the starting operation whenever the required starting current exceeds an adjustable predetermined value, the starting operation being resumed when the current falls below this limit. There are several forms of current-limit acceleration self-starters, and only those which are most widely used will be described.

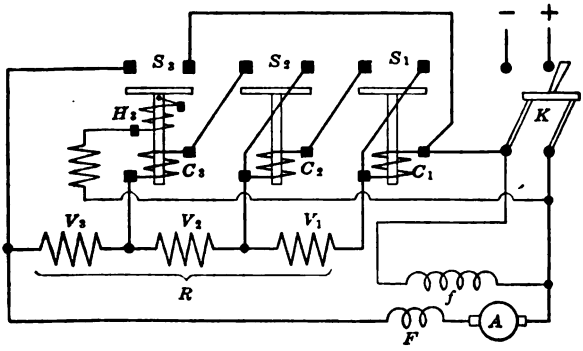


FIG. 64.—Starting device using the series switch of Fig. 63.

515. **A series switch operating magnet** is shown in Fig. 63; this piece of apparatus is designed to accomplish the current-limit acceleration of direct-current motors. The series switch is operated by an electromagnet, which, as the name of the device indicates, may be connected in series with the motor. The magnetic circuit enclosing this winding may be of the

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solenoid or clapper form, but invariably includes a section of restricted area, "*A*," bridged by a movable element, "*B*," which gives a maximum shunting effect when the switch is open, and a minimum shunting effect when it is closed. An adjustable air gap is included in the magnetic bridging circuit. Whenever the current passing through the winding is in excess of a certain value, that section of the magnetic circuit ("*A*") which is of restricted area will be saturated, and the excess flux lines set up by the winding will, therefore, seek the other path and tend to hold the switch in an open-circuit position. The switch remains open as long as the current in the magnetising winding is above the value for which the switch is adjusted; below this value the restricted area becomes capable of carrying a sufficient proportion of the flux to set up a counter force capable of overcoming the restraining pull, and close the switch.* The solenoid-type series switch is quite fully illustrated and described in the *Transactions*, of A. I. E. E., Vol. XXX, page 1563, in a contribution by A. C. Eastwood.

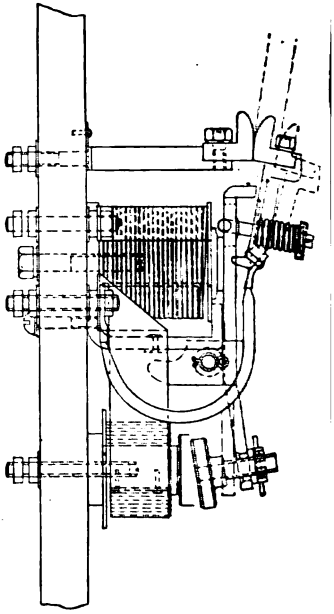


FIG. 65.—Magnetic lock-out switch.

Fig. 64 is a typical connection diagram for a self-starting device made up of these switches. When the line switch "*K*" is closed, current passes from the positive line through the shunt-field windings, "*f*," to the negative line; also from the positive line through the armature, "*A*," the series field, "*F*," the resistance sections, "V_3" "V_2" "V_1," and the operating coil, "C_1" of the first series accelerating switch, to the negative line. If the initial current inrush is in excess of the value at which "C_1" locks open, no resistance will be cut out until the accelerating current has fallen to the point which will permit "C_1" to lift its plunger. When "C_1" lifts its plunger, switch "S_1" is closed, thereby short-circuiting resistance section "V_1" and including the winding "C_2." The operation of these series switches is progressive. When "C_3," the last of the accelerating windings, closes its switch "S_3," windings, "C_1," "C_2" and "C_3," are short-circuited and the shunt winding, "H_3," is connected in circuit directly across the lines. Winding "H_3" serves to hold "S_3" closed during running, thus guarding against the dropping out of the accelerating switches should the motor operate under light load.

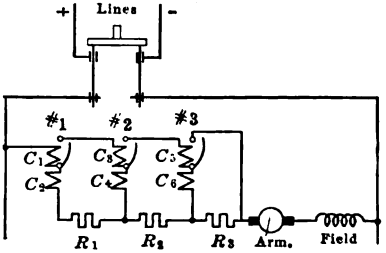


FIG. 66.—Starter comprising three magnetic lock-out switches.

* Par. **541**, No. 29.

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516. The magnetic lock-out switch, illustrated in Fig. 65, is applicable to direct-current motors. It is a clapper-type switch of conventional form, operated by a series winding instead of shunt, and having a second series winding, separately mounted, adapted to act on a downwardly projecting extension of the switch clapper, and to hold the switch open as long as the force exerted by this secondary winding exceeds that of the closing coil. An adjustment is provided by which the air gap between the secondary or locking-out coil and its armature can be varied; thus the current above which the switch will be locked in an open position can be adjusted through a wide range.

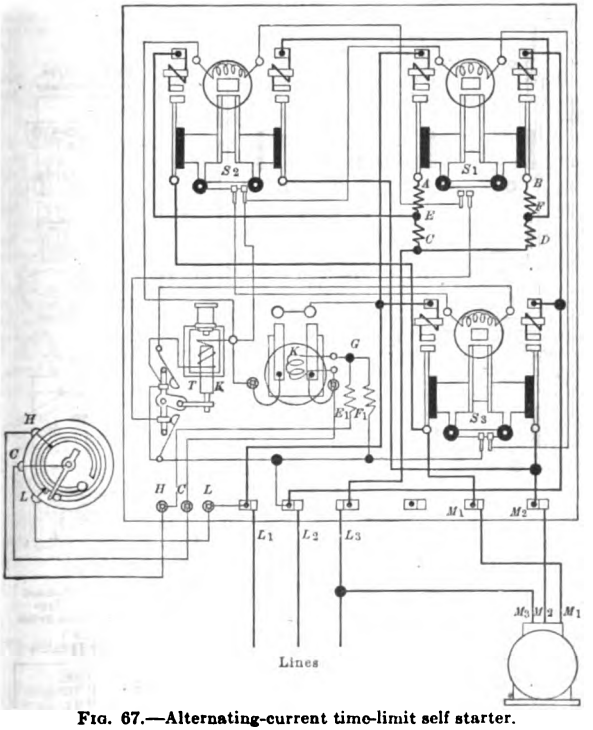


FIG. 67.—Alternating-current time-limit self starter.

Referring to the diagram, Fig. 66, which covers a simple starter consisting of three magnetic lock-out switches, it will be noted that when the line circuit is closed, the motor current passes from the positive line through the two windings of the first magnetic lock-out switch, thence through three sections of starting resistance to the armature of the motor to be started. As long as the current passing through these windings is in excess of a predetermined and adjustable value, the restraining force exerted by the lower or locking-out magnet will exceed the attractive force exerted by the upper or closing magnet, and the switch will maintain an open-circuit position. When the current has fallen below this predetermined value, the upper or closing

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magnet will develop sufficient pull to overcome the lock-out winding. As soon as the contacts of the switch engage, one section of the starting resistance is removed, and, with this section, the lock-out coil, so that any tendency which this coil might have to hold the switch in an open-circuit position is entirely removed. No. 1 accelerating switch, in closing, not only short-circuits a section of the resistance and its lock-out coil, but also automatically includes both windings of the second accelerating switch which in turn locks open until the starting current has fallen below the value at which it is adjusted to operate. These switches will remain closed with 5 per cent. of their normal current; consequently no shunt winding is ordinarily required for the last switch.

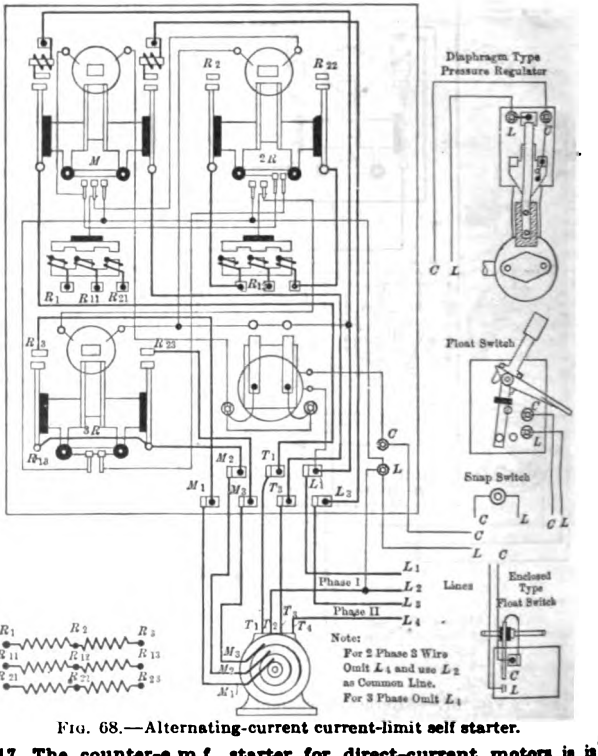


FIG. 68.—Alternating-current current-limit self starter.

517. The counter-e.m.f. starter for direct-current motors is in reality a current-limit starter. In this device the starting resistance is removed by a series of magnetic switches whose operating windings are connected across the motor armature; these switches close successively as the counter e.m.f. of the motor increases with the speed.

518. Alternating-current induction self starters may also be of either the time-limit or current-limit type. In the former the primary windings are connected to the starting transformer for a predetermined length of time,

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nd are then thrown directly on the line. Fig. 67 shows a typical starter of his class. A very similar starter is employed for the control of secondary tarting resistance, the removal of the starting resistance being accomplished fter a predetermined time interval. Both induction and primary-resistance elf starters of the current-limit type are manufactured, but have not proven s satisfactory as the time-acceleration type on account of the low starting orque of squirrel-cage motors, and the possibility of their being so loaded hat they will not accelerate sufficiently to enable a current-limit type of tarter to change from starting to running position. Fig. 68 shows a current-imit acceleration controller for use in connection with an alternating-current lip-ring motor. This controller consists of a primary contactor and two econdary resistance contactors, all of which are double-pole type. The peration of the primary contactor may be controlled by a pressure regulator, float switch, or a simple snap switch. The secondary resistance switches re arranged for successive operation, and are governed by two 3-phase, econdary series relays, which are arranged to halt acceleration whenever the notor current exceeds the value for which they are adjusted.

SPEED REGULATORS

519. Direct-current speed regulators. The speed of direct-current motors may be varied in two ways: first, by varying the potential impressed at the armature terminals, the field strength remaining constant (the speed of a direct-current motor operating at constant field will be directly proportional to the voltage impressed on its armature terminals); second, by varying the field strength, the voltage at the armature remaining constant. The speed of a motor whose armature potential remains unchanged, will be inversely proportional to the field strength. Speed control can also be obtained by a combination of the two methods just mentioned.

There are many ways in which the armature potential may be varied, the most common being to insert a resistance in the armature circuit; the *IR* drop, across this resistance serves to reduce the voltage impressed upon the armature. This method is open to the objections that it is inefficient and that the *IR* drop varies with the motor load; consequently the regulation is not good and only a limited range of regulation can be obtained. Assuming a motor to be operating under full-load torque, about 125 per cent. of full-load current will be required to start it, and the amount of resistance which will permit such a current inrush will give 75 per cent. reduction in armature e.m.f. and speed with full-load torque and current. It may therefore be said that 4 to 1 is the maximum speed range which it is possible to obtain satisfactorily by the armature-resistance method, and that in many cases 3 to 1 will be the maximum range obtainable. The regulation with this method at reduced speed, under variable loads, is so poor as to make armature-resistance speed regulation impracticable for any but constant-load work.

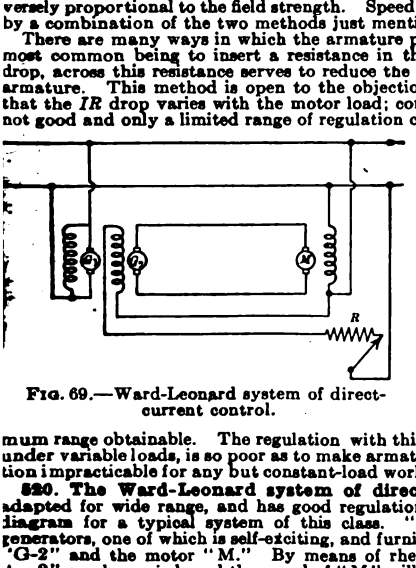


FIG. 69.—Ward-Leonard system of direct-current control.

520. The Ward-Leonard system of direct-current control is well adapted for wide range, and has good regulation. Fig. 69 is a connection diagram for a typical system of this class. "G-1" and "G-2" are two generators, one of which is self-exciting, and furnishes current for the fields of "G-2" and the motor "M." By means of rheostat, "R," the voltage of "G-2" can be varied, and the speed of "M" will be correspondingly varied. The regulation of such a system is very good, through a wide range of control, and becomes unsatisfactory only when the comparatively small *IR* drop in the armatures "G-2" and "M" and the connections between them, becomes a large percentage of the total potential generated by "G-2" (Par. **541**, No. 4).

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By reversing the fields of "G-2," the direction of rotation of the moto "M," can be changed (Par. **541**, No. 19, 21 and 24). This system is exte sively employed for reversing mill and mine hoist duty.

521. The multiple-voltage method of direct-current speed contr is generally used in connection with a certain amount of field control. Th older multiple voltage systems are almost invariably four-wire, as per Fi 68. A balancer set having three armatures is connected across a 250-vo system and gives 60, 80 and 110 volts between the three sets of mains. The motor whose speed it is desired to control, may obviously be so connected that it will have 60, 80, 110, 140, 190 or 250 volts impressed on its armature. Field control is used to smooth out the steps; the motor field strength is reduced while the armature is connected to each potential, before stepping to the next higher potenti and is increased to normal strength as the change is made.

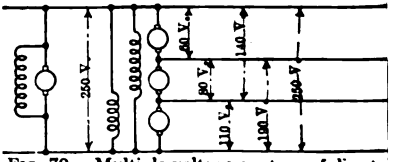


FIG. 70.—Multiple voltage system of direct-current control.

Later systems employ but three wires (Par. **541**, No. 5) and provide f 110 and 220, or 125 and 250 volts at the motor armature. To obtain reaso ably small speed increments throughout the entire speed range, these thre wire systems require a motor whose speed may be varied by field contr through a wider range than is required where a motor is operated on the fou wire system.

522. The field strength of a motor may be varied by electrical o mechanical means. When this is accomplished electrically, the field strengt is generally varied by a field-regulating rheostat. Field regulation is effecte mechanically by changing the air gap and consequently the reluctance of th field circuit. Either method produces the same results, the former havin the advantage that the regulating rheostat can be conveniently located a some distance from a motor, also that the field strength can easily be increase to normal during starting.

The extent to which the speed of a motor can be varied by field contro depends upon its design. Generally speaking, a standard machine wil seldom commutate well if its speed is increased in this manner more than 2 per cent., while specially designed inter-pole motors have been built for speed ranges as great as 10 to 1. On account of their good inherent regulation and their high efficiency at all speeds, field-control motors are almost universally employed where speed control of direct-current motors is required.

523. A combination of armature-resistance and field control may be used to advantage where reduced speeds are required for comparatively short periods, and the expense of installation can be materially reduce by such procedure. It will also be found where a wide range of speed is required in connection with the Ward-Leonard system (Par. **541**, No. 18, Fig. 67, that it will be advisable to regulate the field strength of the motor as well as that of the generator.

524. Self-starting speed regulators. In machine-tool practice, self-starters are used to start and stop machines whose speeds are adjustable by a regulator controlling the motor fields. Such self starters may be equipped with a vibratory field-regulating relay, the winding of which is connected in series with the motor armature. When the armature current reaches a predetermined value this relay will short-circuit the field rheostat, thus increasing the motor field strength to normal. The field strength is continued at normal until the armature current decreases sufficiently to allow the relay to drop, thus inserting the field resistance and increasing the armature current because of the reduced counter e.m.f. Increase in armature current causes the relay again to short-circuit the field rheostat, and the relay continues to vibrate, alternately short-circuiting and cutting in the field resistance, until the motor has accelerated to such an extent that the field resistance may be left in circuit without causing the armature to take a current in excess of the relay setting.

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525. Series-parallel control of two motors is a convenient and efficient ans of obtaining two speeds, one speed being one-half the other. Such ontrol system has the added advantage of reducing the current required to duce a given starting torque. This system of control is most widely d in railway work (also see Par. **541**, No. 10).

526. Speed control of squirrel-cage motors may be accomplished in) ways: first, by changing number of poles; second, by varying the com- ed voltage and frequency pressed on the primary. e number of poles may be nged by the use of sepa- e windings and selective rgisation, or by regroup- the windings to change number of poles. The ner method is employed re more than two speeds required. To obtain a 1 2 ratio the windings are erally connected as shown in Fig. 71. It should be particularly noted t in changing from the star, or half-speed connection, to the double star, ull-speed connection, it is necessary to reverse two of the incoming lines rder to prevent the motor from running in a reverse direction.

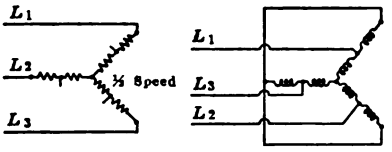


FIG. 71.—Two-speed squirrel-cage motor.

Where voltage and frequency are changed they must be varied in the same o, *i.e.*, for half speed, half voltage and half frequency. The speed of the irrel-cage motor *cannot* be varied by the use of primary resistances.

527. A combination of variable frequency and change of poles is netimes found effective. For example, a system employing a 10-pole/20- e, 440-volt, 60-cycle motor at 720 rev. per min. (maximum synchronous ed), may be used in connection with two frequency-changing sets, and the owing speed range obtained:

60 cycles	440 volts	10 poles	720 rev. per min.
45 cycles	330 volts	10 poles	540 rev. per min.
60 cycles	440 volts	20 poles	360 rev. per min.
45 cycles	330 volts	20 poles	270 rev. per min.
30 cycles	220 volts	20 poles	180 rev. per min.

The horse-power output of motors used with such a control system is ctly proportional to the speed at which they operate.

528. Slip-ring motors can be varied in speed by the use of secondary stance. This method of speed regulation is open to several objections. is not efficient, and the speed regulation at reduced speeds is not good, ause the amount of speed reduction obtained with a given amount of ondary resistance in circuit varies directly with the load which the motor arrying. Under the most favorable conditions it is not commercially sible to obtain a greater reduction in speed than 75 per cent., and in most es 50 per cent. reduction in speed will be found to be the practical limit. lip-ring motors are sometimes constructed with means for varying the nber of poles, either by the use of multiple windings, or by regrouping the idings. Since both the primary and the secondary windings must be trolled, such systems are commercially impracticable for most small tallations, but are used to some extent in rolling-mill work.

529. Concatenation control of induction motors. The speed of two ernating-current induction motors mounted on the same shaft may be led by connecting them in cascade, or, in other words, by operating in catenation (Sec. 7). The first motor of such a system must be of the ring type, and the second may be of the squirrel-cage type, although the of a slip-ring machine is preferable on account of the possibility it affords obtaining higher starting torques and reduced speeds. With two con- enated motors, Fig. 72, a total of four economical running speeds can be ained, as follows: one with motor "*A*," connected to the line; the second h motor "B" directly on the line; the third with "A" and "B" in direct catenation, and the fourth with "A" and "B" in differential concatena- . Motors are said to be in direct concatenation when they tend to

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revolve in the same direction and in different concatenation when the secc ("B") tends to oppose the first ("A"). See also Par. **541**, No. 6. T synchronous speed for each of the concatenated connections can be det mined as follows:

$$S = \frac{\text{cycles} \times 120}{P_1 \pm P_2} \qquad \text{(rev. per min.)}$$

where S is the synchronous speed in rev. per min.; P_1 is the number of po of motor "A;" P_2 is the number of poles of motor "B." The plus si should be used when the motors are in direct concatenation, and the mir sign when in differential concatenation. The diagram in Fig. 61 shows connections for a cascade system.

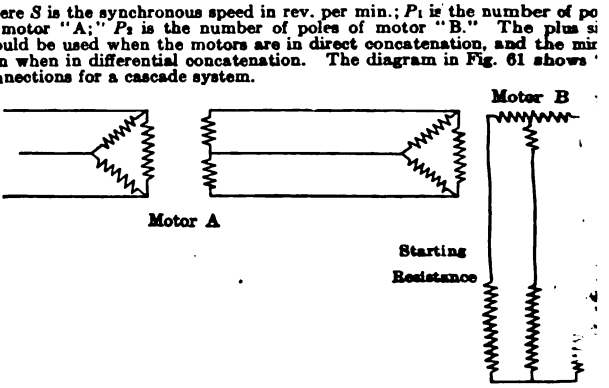


FIG. 72.—Cascade connection of two motors.

There are so many methods by which the speed of one or more slip-ri motors can be varied (see Par. **541**, No. 6, 7, 15 and 20), that it is impossi to cover them all in the limited space available.

530. Single-phase motors of the repulsion type may have their spe varied either by the use of primary resistance, or by shifting the brush The results obtained by various motor manufacturers are so widely diver as to make it almost impossible even to outline the limitations of su systems.

531. Synchronous motors are not susceptible of speed control; see Pa **541**, No. 22.

ELECTRICALLY OPERATED BRAKES

532. Classification. In the control of electric motors it often becom desirable to provide a brake which is electrically released and applied by spring or weight. Such brakes are made in three types—the multiple-di the band and the shoe type.

533. Band brake. In one type of band brake, a wheel is attached to t shaft to be braked, and this wheel is encircled by a band lined with a su able friction material. Normally the band is brought into frictional engag ment with the wheel by means of a spring; a solenoid is provided for the pose of compressing these springs and relieving the brake band. The b brakes are manufactured for either alternating-current or direct-curr service.

534. A multiple-disc brake is illustrated in Fig. 73. This typical f of brake is manufactured only for direct-current service. It consist a hub which is mounted on the shaft to be braked, to which hub are ke one or more discs and a stationary frame, in which are carried, by means keys, two or more stationary discs. Normally the rotating discs are clam between the stationary discs by the action of a spring, and by means o electromagnet this spring can be compressed and the pressure on the fric discs relieved.

535. Shoe brake. A typical shoe brake differs from the band brake i in that the movable friction face is in the form of a shoe rather than in

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a band. These shoe brakes are also made for alternating-current or current service.

Advantages of the various types. The disc brake has the advantage over either other type, of imposing no side strains on the shaft to which

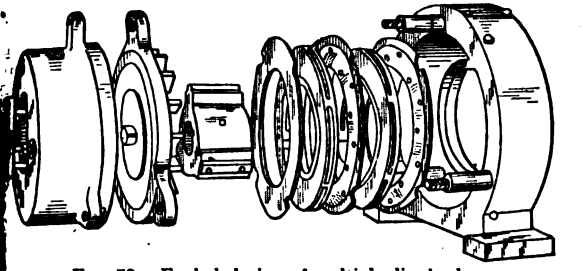


FIG. 73.—Exploded view of multiple-disc brake.

plied. Naturally, it also provides equal braking for either direction tion, whereas some forms of band and shoe brakes do not possess this The band-type brake, generally speaking, is superior to the shoe- because of the larger proportion of the brake wheel which is in actual e, and the consequent reduction in unit pressure on braking surfaces. over the band-type brake possesses the tendency to wrap itself around wheel; consequently it can operated by means of a naller solenoid than is re- uired for a shoe brake of rresponding rating.

DYNAMIC BRAKING

537. Classification ynamic braking may be de- ned as the retardation of a achine by a motor acting as generator, which takes no rrent from the line other an for excitation. The sub- ct of dynamic braking may divided into two parts as llows: first, for the purpose effecting a quick stop; cond, for the retardation of descending load.

538. For the purpose of tarding the descending ad on cranes and ore-hand- g machinery, it is common actice to employ dynamic raking. The motors used for is service are almost invaria- ly series-wound, and in start- g down it is necessary to take rrent from the line by a separate circuit in order to energise the series field. he systems employed are almost innumerable, and it is impossible to de- ribe them all here. The connection diagrams, Fig. 74, illustrate the heory of a control system of this character. It will be noted that in hoist- g, the motor armature and field are first connected across the line in series ith a resistance. This resistance is removed step by step as the control ver is advanced toward the full-speed position. A mechanical brake set by weight or spring serves to hold the load in any position, and a series-

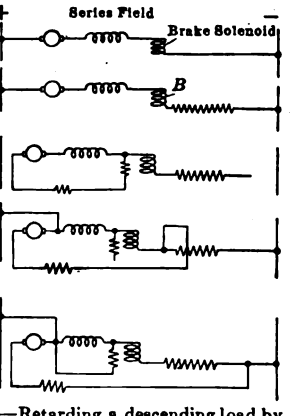


FIG. 74.—Retarding a descending load by dynamic breaking.

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wound solenoid, "B," is adapted to release this mechanical brake wh hoisting or lowering is taking place. In the "off" position, the circuits both motor and brake solenoid are open, and consequently the mechanic brake is set. In the lowering positions the motor field and the brak solenoid are connected across the line in series with a variable resistanc the motor armature is bridged across the field and the brake solenoid. A the control lever is advanced toward the full-speed lowering position, th resistance included in the field-brake circuit is increased until all the resi tance is inserted. Further movement increases the resistance included b tween the armature and the series field until the armature is finally connect directly to the line. The higher the resistance included in the armatu circuit, the greater will be the speed at which a given load will descend; a the lower the value of resistance included, the lower will be the descendi speed. Should the descending load be insufficient to overhaul the motor, t latter will run as a shunt-wound machine, and actually drive the hoist drum in a reverse direction, paying out line to the descending hook. For sendi a light hook down at high speed, the series field is weakened by shunting

539. Dynamic braking of direct-current motors for the purpose effecting a quick stop is employed quite extensively in connection wi elevators, printing presses and machine tools, centrifugal extractors, e The arrangement generally provided consists of a switching appliance connecting a fixed step of resistance across the terminals of the motor arm ture after the line circuit is interrupted. As a result of this procedure t motor acts as a generator and serves to retard and stop the machine which drives. While it is possible to effect a quicker stop by this method than i were not employed, it does not provide for the quickest stopping that c be obtained; it is obvious at once that as the motor speed decreases, the pot tial generated by its armature correspondingly decreases, and the reducti in current which the armature will send through the fixed step of resistan results in a gradual diminution of the braking force, until it reaches a when the armature stops.

Inductive resistance is often employed in the braking circuit for the pu pose of prolonging the period during which the braking current remains high value, and quicker stoppage can be effected by its use. Where t quickest possible stop is desired, a variable resistance should be connect across the motor armature; this resistance should be reduced by a series magnetic switches, the successive closure of which will be halted whenev the braking current exceeds a predetermined value. With such an equi ment, the braking current can be maintained at a high value throughout t entire stopping period, and much faster results obtained than are possible any other method. In the interest of economy the starting resistance a the accelerating switches are generally employed for graduated dynam braking. Thus the same apparatus which is used to limit the current acceleration, serves also to limit the current of retardation.

540. Alternating-current motors can be used for dynamic braki only when direct-current is available for their excitation; the method seldom used, for this reason. For quick stopping, the reversal of the prima and the inclusion of a high resistance in the secondary is equally effect and does not require direct current. For the retardation of descendi loads it has not been very popular, largely on account of the general unpo larity of alternating-current motors for this class of service, direct-curr machines being better adapted on account of their inherent characteris (Par. **541**, No. 11).

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SECTION 16

ELECTRIC RAILWAYS

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SECTION 16

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INTRODUCTION

1. Considerations affecting general design. All railway estimates are based upon the performance of the rolling stock, as this determines the type of equipment to be used, its capacity, the possibilities of schedule speed, and the power input to the train, both maximum and average. The last-named factor in turn determines the characteristics of the low-potential distribution system, whether trolley or third-rail, and its capacity. These considerations lead up to the determination of substation capacity and finally, the capacity and cost of the generating station. It is important therefore, that the characteristics of the different types of motive power be thoroughly understood, as a false assumption or error in the preliminary calculation of motive-power capacity and train energy consumption may lead to very serious errors in laying out the entire generating and distributing system.

2. Classification of systems now employed. There are four types of **motors** available for railway service, giving rise to three systems of distribution: (a) the direct-current series-wound motor used at line voltages of from 600 to 3,000 volts, fed from a synchronous-converter or motor-generator substation, tied into a high-potential three-phase alternating-current transmission system; (b) the alternating-current series-wound motor fed directly from an alternating-current high-potential transmission system through intermediary step-down transformers; (c) the alternating-current three-phase induction motor fed directly from an alternating-current three-phase transmission system through step-down transformers; (d) the alternating-current polyphase induction motor, fed from a single-phase circuit through an intermediate phase converter ("split-phase system").

All four systems enjoy the advantage of alternating-current generation and transmission of power at high potential, the direct-current and induction motor system demanding multiphase generation, while single-phase generation and distribution best serves the needs of the single-phase alternating-current motor and split-phase systems.

3. Method of studying traction problems. The various steps to be followed in the determination of the proper relation of motive power equipment, distribution and generating systems, are as follows: (a) a knowledge of train-resistance values; (b) calculation of possible schedule with the frequency of stops, train weight and other fixed factors entering into the problem; (c) determination of train input as obtained from train resistance and energy consumption values; (d) determination of motor capacity; (e) calculation of train diagrams; (f) determination of capacity of low-potential distribution system and substations; (g) determination of generating-station capacity; (h) estimate of cost of the various parts of the electric railway system determined by the capacity found above; (i) approximate cost of operation; (j) approximate gross income as determined by comparative statistics; and dividend earning power of road.

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TRAIN RESISTANCE

4. Tests. Careful experimental tests, carried out during the past few years with electric locomotives and motor-cars, have thrown new light on the much discussed question of train resistance at the higher speeds. Without, in any way, disparaging the care taken in tests made with steam locomotives, it was not until electrical methods of measuring power introduced greater accuracy than was possible by use of the steam indicator, that consistent results became obtainable with light trains operating at very high speeds.

The electric motor was the means of introducing the single-car train operating at speeds up to 70 miles per hr. At that time no data were extant concerning the operation of single-car trains. It was soon found that such a car operating alone required an input out of all proportion to the power required to propel a train composed of several such cars operating at the same speed, consequently new adjustments had to be made in train-resistance formulas then existing.

During the spring of 1900, a series of tests were made by Mr. W. J. Davis, Jr., on the Buffalo & Lockport Railway, which consisted in running a 40-ton electric locomotive alone and with trailers at speeds approaching 60 miles per hr., as a maximum. These tests probably constitute the first consistent attempt to utilise the benefits of greater accuracy which electrical methods of recording afford. Since then other tests, taken under better conditions and with various classes of equipment, afford data from which it is possible to predict, with a considerable degree of accuracy, the total resistance (wind, bearing and rolling) opposing the movement of cars or light trains up to speeds of 100 miles per hr.

5. Train resistance may be expressed in pounds tractive effort exerted at the rim of the driving wheels of the prime mover of a train. It includes all losses in bearings, losses due to rolling friction, bending rails, flange friction, etc., and the wind-resistance loss. The last item is made up of head-on resistance, skin or side resistance and eddy currents caused by the suction at the rear of the car or train. All these variables depend upon the condition of bearings, design of trucks, condition of the road-bed, shape and cross-section of cars, direction of wind, etc., so that any tests, to furnish authoritative data, must be sufficiently comprehensive to eliminate the errors of purely local conditions. As no such elaborate series of tests have yet been made, any formulas predicated on the data available must at best be approximate.

Data are available on the performance of locomotives and cars of modern construction as follows: Buffalo and Lockport experiments in 1900; Zossen high-speed tests in 1902–3; tests on New York Central type locomotive at Schenectady, 1905–6; tests on car No. 5 at Schenectady, 1906; tests made by the Electric Railway Test Commission, on the test car "Louisiana," 1904–5; New York Subway tests, 1905; Dynamometer car tests by Prof. Edward C. Schmidt, University of Illinois, 1910, and by Schmidt and Dunn in 1914 and 1917.

Many isolated tests have been made from time to time other than those mentioned above, but either the data was not sufficiently complete or the conditions were too unfavorable to justify using the results obtained as applying to other than local conditions. The data comprised in the tests given above are sufficiently general, as they include the operation of trains varying from a single 35-ton car, to a train of 532 tons, and at speeds up to 130 miles per hr. in the Zossen tests.

6. Frictional resistance. The laws governing the **friction of journal bearings** are fairly well understood, and such bearing friction opposing the motion of a train, need introduce no undetermined factors in a calculation of train resistance. Such friction losses decrease with the pressure on the bearings and are a function of the speed. Hence, the expression, $f' = A' + B'S$, where f' is bearing friction expressed as lb. per ton, A' and B' are constants determined by experiment (see Par. 8) and S is the speed expressed conveniently in miles per hr. **Rolling friction** (see Par. 22) is due to the friction of metal rolling on metal where the surfaces are not perfect; the bending of rails due to insufficient support, or meager cross-section of rail; and flange friction between rail and wheel flange. All these factors are proportional to speed, and hence may be represented by a straight line function of speed. As bearing and rolling friction are both approximately proportional to the speed they may constitute the first two terms of a train resistance formula,

$$f_1 = A + BS \quad \text{(lb. per ton)} \qquad (1)$$

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7. The friction constant, A, has been determined by experiment to vary from 3.5 to as high as 12 lb. per ton, depending upon the weight concentrated on the journal bearings. Both the Zossen cars and the New York Central locomotive have indicated in test a value of $A = 3.5$ to 5, both the cars and locomotive having a weight of approximately 200,000 lb. concentrated on twelve journal bearings. Tests on Car No. 5 at Schenectady on the other hand, gave a value of approximately 8.5 for A, this car having 68,800 lb. on eight bearings. Hence, the impossibility of giving a single value to A that will obtain over wide variation in type of equipment.

The factor, A', can be expressed in terms of the train weight and the following purely empirical term is suggested as agreeing remarkably close with experimental results.

$$A = \frac{50}{\sqrt{W}} \qquad (2$$

where W = tons weight of train.

In using such a term it is necessary to limit A to a minimum value of 3.

8. Values of A (Par. 7)

20-ton car	11.2	60-ton car	6.4
30-ton car	9.12	80-ton car	5.5
40-ton car	7.9	100-ton car	5.0
50-ton car	7.07	200-ton car	3.5

9. The friction constant B. The coefficient of S in the second term of the train resistance formula (Par. 6), takes cognisance of the increase of rolling and bearing friction with speed. This coefficient can be determined experimentally by operating a train with and also against a wind of known velocity. Given a wind of say 10 miles per hr. in the direction of the test track, if a series of runs be made at 40 miles per hr. against, and 60 miles per hr. with the wind, the effect of wind resistance would be the same in both cases. On the other hand, any difference in the total train resistance found would measure the (journal and rolling) frictional difference occurring for a speed change of 20 miles per hr. Unfortunately the published data of the Zossen test are incomplete in this respect, and offer no material upon which to place a value for the second term coefficient. Other tests, made for the purpose, give values of B for speeds up to 80 miles per hr. with trains of any composition. As the effect of B is small with heavy trains and almost negligible with single cars operated at high speed, any errors introduced by reason of insufficient data, do not seriously affect the accuracy of the train resistance formula as applied to the classes of equipment commonly met.

Values of B obtained experimentally vary from 0.03 to 0.07, depending upon the type of equipment and condition of track. For practically all operating conditions a value of $B = 0.03$ will give sufficiently accurate results, using higher values of B for very light equipments (under 30-ton cars) and poor track conditions, such as scanty rail, accumulations on rail, etc.

10. Wind resistance. By far the most important term of a train resistance formula (Eq. 4) for light trains is the term expressing the relation between effect of wind and speed of train. It is in this term that the many elaborate tests made with steam locomotives have failed in affording accurate data, especially for very light trains operating at high speeds. Such tests have usually been made either with steam indicator or dynamometer car as the means of determining the effect of wind pressure. The indicator card included in its readings all the intermediate internal friction losses of the locomotives, thus making results obtained by its use of small value when applied to other types of motive power having much smaller internal losses. The dynamometer car, while giving accurate readings of the draw-bar pull required to haul the succeeding trailers, failed to indicate the amount of head-on wind pressure, which constitutes by far the larger proportion of the total resistance opposing the progress of a light train at high speed. Hence the tendency to discard in a large part, the experimental data obtained from steam locomotive tests and place reliance upon the data obtained from such tests as the series listed in Par. 5.

Tests made upon small models (Goss in 1897) and by means of whirling surfaces, seem to indicate that wind pressure increases as the square of velocity.

The Zossen experiments also indicated that the wind effect upon the car increased as the square of the speed, thus following along the line of labora-

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tory experiment and previous experimental train tests by Davis in 1900. Hence, that portion of train resistance which results from the effect of wind may be given by the relation

$$f_3 = \frac{CaS^2}{W} \qquad \text{(lb. per ton)} \qquad (3)$$

where f_3 is the wind resistance in lb. per ton, C is a constant, a is the projected area, and W is the train weight in tons. This equation leads to the third term of Eq. 4.

Values of C (*Kernot*, 1894)

$C = 0.004$ for flat surfaces, $C = 0.0020$ for cylinder,
$C = 0.0024$ for octagonal prism, $C = 0.0014$ for sphere.

11. Method of making wind resistance experiments. The simplest and most accurate is the coasting method, where a moving train is allowed to drift until it reaches standstill, the rate of speed decrease and elapsed time being accurately noted. The efforts of most experimenters have been directed toward securing such data during periods of no wind in order to eliminate this troublesome feature. However, a series of runs taken with and against a wind of known velocity offers much data not otherwise available, and affords a ready means of solving directly for the coefficient of the second and third term of the train resistance formula (Eq. 4).

For example, given a wind of 20 miles per hr. velocity, a series of runs made with and against such a wind will, at say 50 miles per hr. train speed, correspond to a wind pressure at 30 miles per hr. with the wind and 70 miles per hr. against the wind, the rolling friction being constant at the value obtaining at the train speed of 50 miles per hr. As the wind pressure varies as the square of the speed, such a series of tests affords a means of determining the coefficient of S^2 for the particular type of equipment used.

12. The shape of the car end has a large influence upon the coefficient of S^2, such a result being reasonably expected from the results of experiments by Goss, Kernot and others: in fact, Davis checked up the values of 0.004 found by Kernot for flat surfaces. As a matter of fact, no cars or locomotives used for high-speed service have perfectly flat ends, and hence, all experimental values of C have been found to be less than 0.004.

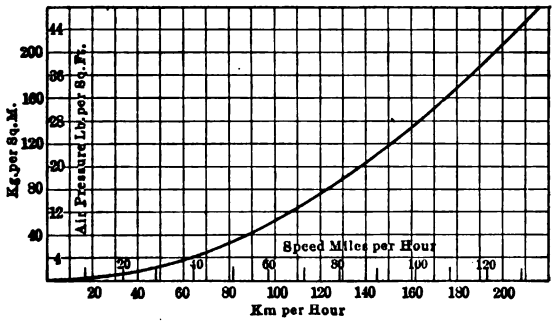


FIG. 1.—Wind-resistance test (Berlin-Zossen).

Little attempt has been made to construct cars for least wind effect, owing largely to a lack of full understanding of the benefits to be secured thereby. The cars used for high-speed suburban service and all electric locomotives, with few exceptions, are provided with partially rounded ends, with the result that the effective wind pressure is considerably reduced. A notable example of the extreme type of pointed nose design is the steel gasolene motor-car No. 7, of the Union Pacific Company, and such construction is a step in the right direction.

Values of C vary from 0.004 with perfectly flat ends to 0.0015 with noses

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of the extreme type, while the average rounded end suburban car and ele trio locomotive with sloping front give rise to values of C from 0.002 0.0025 (see Par. 10).

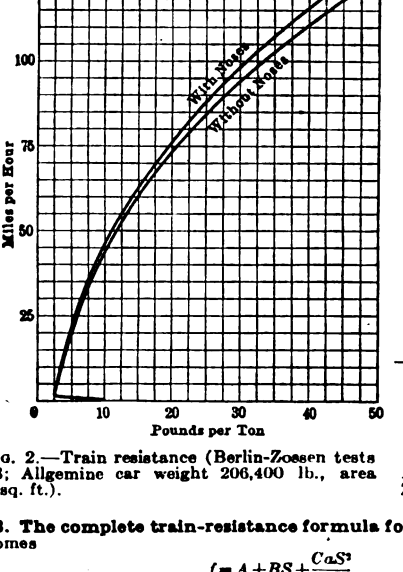


FIG. 2.—Train resistance (Berlin-Zossen tests 1903; Allgemine car weight 206,400 lb., area 130 sq. ft.).

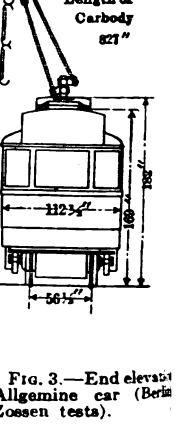


FIG. 3.—End elevati Allgemine car (Berli Zossen tests).

13. The complete train-resistance formula for single-car operati becomes

$$f = A + BS + \frac{CaS^2}{W}$$

$$= \frac{50}{\sqrt{W}} + 0.03S + \frac{0.002aS^2}{W}$$

wherein S is the speed in miles per hr.; a the cross-section in square fe and W the car weight in tons.

It was found by Davis that somewhat larger coefficients for B and obtained from the limited data of the Buffalo and Lockport tests, but mu subsequent data seem to indicate values of $B = 0.03$ and $C = 0.002$ for ca weighing not less than 40 tons and having partially rounded ends.

14. Comparison of calculated car-resistance with the actual te values

(Zossen experiments)*

Speed miles per hr.	10	20	40	60	80	100	12
$A = 4.92$	4.92	4.92	4.92	4.92	4.92	4.92	4.9
$BS = 0.03S$	0.30	0.60	1.20	1.80	2.40	3.00	3.6
$\frac{CaS^2}{W} = \frac{0.002S^2 \times 128}{103.2}$	0.25	1.00	3.96	8.93	15.99	24.80	35.7
F (calculated) =	5.47	6.52	10.08	15.65	23.22	32.72	44
F (observed) =	3.5	5.5	9.10	14.9	22.8	33.3	46

* Here $a = 128$ sq. ft. and $W = 103.2$ tons (2,000 lb.).

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It is very possible that the higher values obtained at the maximum speeds were influenced by reason of the track being not rigid enough for speeds of 120 miles per hr., and hence increasing the value of B.

15. A consideration of trains of several cars makes it necessary to introduce an additional factor in the third term of the proposed train-resistance formula that shall express the effect of the wind resistance upon the sides of the succeeding cars. The head-on wind resistance is borne by the leading car, and hence additional cars only introduce the additional skin friction offered by a train of greater length.

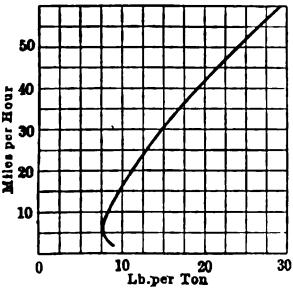


FIG. 4.—Train resistance (General Electric tests); weight 63,000 lb.

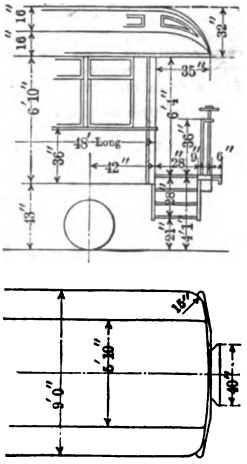


FIG. 5.—Elevation and plan, car No. 5 (General Electric tests).

16. The most reliable and exhaustive series of tests made with trains composed of a different number of cars is offered in the experimental runs of the New York Central locomotive No. 6,000, during its 50,000-mile endurance run, hauling trailers up to a nine-car train. Over 140 runs under different climatic conditions are condensed in the series of curves shown in Fig. 6, where the train resistance is expressed in pounds per ton weight of total train including locomotive. This set of curves indicates very plainly the reduction in train resistance per ton of train with the increase of train weight, such a reduction being largely due to the fact that the head-on wind resistance remains constant for any composition of train, being influenced only by the shape and cross-section of the locomotive.

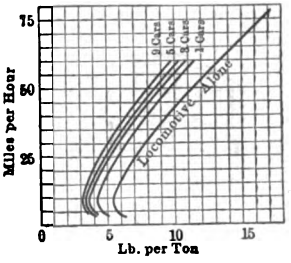


FIG. 6.—Train-resistance runs (N. Y. C. locomotive and train).

17. The increase in skin friction along the surface of succeeding cars corresponds closely to 10 per cent. of the value of wind resistance as expressed by Eq. 3, and for a train of several cars the expression for wind resistance becomes,

$$f_3 = \frac{CS^2a}{W}\left(1+\frac{n-1}{10}\right) \quad \text{(lb. per ton)} \qquad (5)$$

where n represents the number of cars in the train. This may be substituted for the third term of Eq. 4.

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18. The complete formula for any weight and composition of train (see Par. 23) now becomes,

$$f = \frac{50}{\sqrt{W}} + 0.03S + \frac{0.002aS^2}{W}\left(1 + \frac{n-1}{10}\right) \quad \text{(lb. per ton)}$$

The above formula is presented as being an expression of the knowledge of train resistance with the data extant, but any such formula is largely empirical, and is subject to change from time to time as the results of additional tests become available.

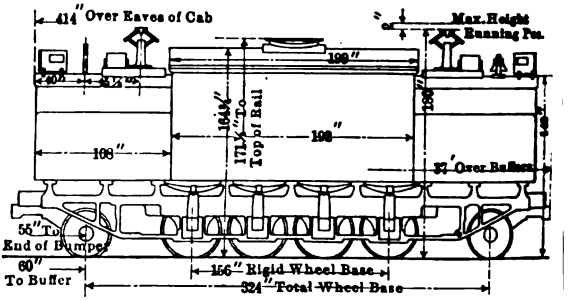


FIG. 7.—N. Y. C. locomotive, side elevation.

Figs. 9 to 13 show curves based upon this train resistance formula, and express the resistance encountered with cars of from 20 to 60 tons weight operating singly and in trains. Also, for high-speed locomotive service, a series of curves is plotted for train values up to nine-car train operation. All these results assume a perfectly level tangent track, free from any foreign matter, such as street accumulations, sand, snow, etc. The effect of such matter is to increase seriously the value of B, hence the curve values should be increased if conditions are unfavorable.

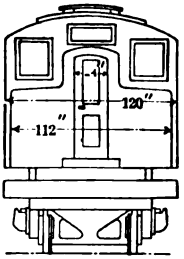


FIG. 8.—End elevation.

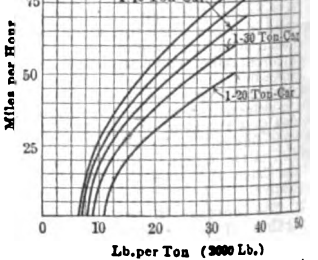


FIG. 9.—Train resistance, single-car train.

19. Freight train resistance is but little affected by wind resistance owing both to the low speeds of such trains and due also to the small cross section of the car compared to the length of the train. What wind resistance is offered is therefore largely skin friction.

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The results of a series of dynamometer car tests conducted by the Engineering Experiment Station of the University of Illinois, are given by Prof. Edward C. Schmidt in a paper read before the A. S. M. E., May 14, 1910. These tests covered a wide range of car weights and train speeds; Fig. 14 gives the results thereof.

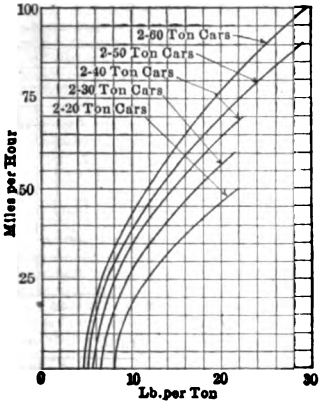


FIG. 10.—Train resistance, two-car train.

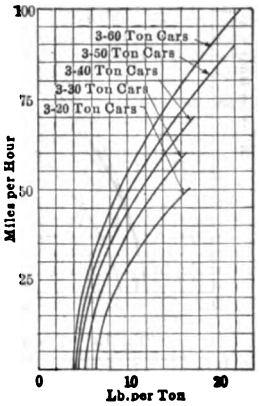


FIG. 11.—Train resistance, three-car train.

20. Track curves are usually expressed in degrees; a 1-deg. curve is taken arbitrarily as one in which a 100-ft. chord will subtend an arc of 1 deg. or, which is the same thing, will subtend a 1-deg. angle at the centre. Hence the radius of a 1-deg. curve is approximately $(100 \times 360)/(2\pi) = 5{,}730$ ft. Similarly the radius of any curve in feet is approximately 5,730/No. of deg. In the metric system a chord of 20 meters is used instead of a chord of 100 ft.; hence the radius of a 1-deg. curve metric is $360 \times 20/2\pi = 1{,}146$ meters $= 3{,}758$ ft. which is equivalent to 1.525 deg. U. S. A.

21. Curve location. This custom of rating curves by degrees instead of by radius has undoubtedly arisen from the facility offered for laying out a curve in the field with a transit. For instance, a transit is set up at the point of curve, *PC* (Fig. 15), and several angles, EAB, BAC, etc., each equal to one half the degree of the curve are laid off. In the first of these directions 100 ft. is measured off and a stake driven. From this stake another 100 ft. is measured off and lined in by the transit in its second position. One-hundred-foot chords are thus laid off until point of tangent *PT* is reaced. As indicated in Fig. 15, this point is seldom at an even station, but is always indicated by a stake marked as shown, *PT*. Sta. 102+80. Likewise with the point of curve, *PC*. In case the *PC* is not at an even

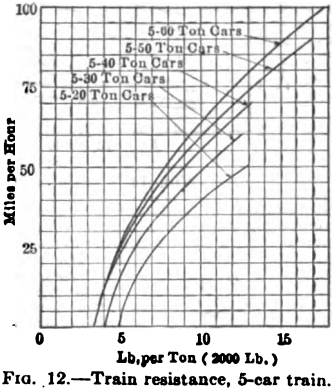


FIG. 12.—Train resistance, 5-car train.

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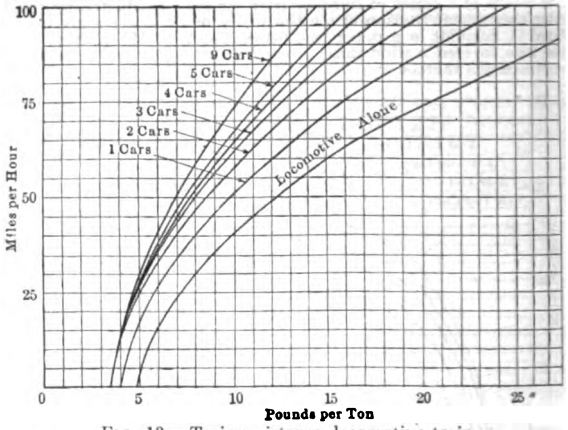


FIG. 13.—Train resistance, locomotive train.

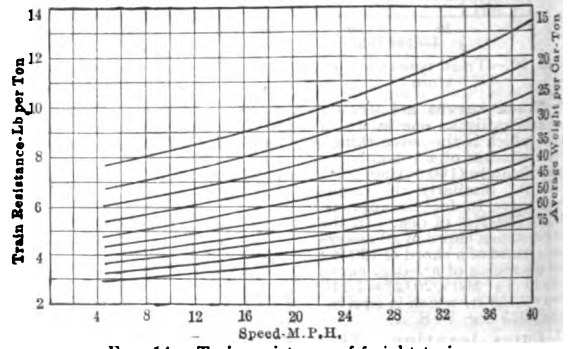


FIG. 14.—Train resistance of freight trains.

station, the first stake of the curve is driven at an even station so that the remaining stakes of the curve will come at even stations. When the curve is sharp, intermediate stakes are necessary and are driven at fractional distances.

It is evident that as the degree of curvature increases, this method of laying out a curve becomes less accurate and not particularly expeditious; therefore, the **sharp curves** met in city streets are generally rated as special work and are laid out and assembled in the works of the switch manufacturers before they are shipped, in which case the curves are generally rated by radius.

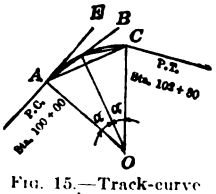


FIG. 15.—Track-curve lay-out.

22. Curve friction. In rounding a curve, the rolling friction of a car is increased due to the increased flange friction, this increase being approximately at the rate of 1.0 lb. per ton for each degree of curvature. As curves are of necessity of limited length they do not become a serious factor in train

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resistance calculations except in the calculation of locomotive constants assigned to mountain grade service, where both sharp curves and heavy grades occur.

23. Grades are expressed in percentages, being the ratio of the distance the train is raised to the distance travelled, in other words, the ratio of the ordinate of a right-angled triangle to the hypothenuse. A grade of plus 1 per cent. is one where the train is raised vertically 1 ft. for each 100 ft. travelled; a minus 1 per cent. grade is one where the train falls 1 ft. for every 100 ft. of distance travelled. It follows that a plus 1 per cent. grade calls for a tractive effort of 20 lb. per ton, while a minus 1 per cent. grade is equivalent to delivering a tractive effort of 20 lb. per ton to the train.

Where gradients are small it is not necessary to consider the reduction in train weight due to the angle of direction of travel to the true horisontal in calculations of friction (Par. 6) and adhesion (Par. 28). However, with the excessive grades, it is necessary to correct for effective train weight.

Grades are divided in railway parlance into virtual grades and ruling grades.

24. Virtual grades are of limited length and are so called as they express the equivalent grade, a value always something less than the true grade. A train running at constant speed can surmount a certain grade as determined by the maximum tractive effort available. The moving train however may be compared to a fly wheel, and has stored in the moving mass a large amount of energy, which is usually expended in heating the brake shoes during the period of stopping. This stored energy may be used to furnish the extra tractive effort required to ascend a heavier grade than the available locomotive tractive effort alone would permit, but in such a case the grade must be of short length. Hence, the actual grade may be considerably in excess of the virtual grade, provided it is so short that the inertia of the moving train can supply the additional energy required to ascend it.

25. The ruling grade means the maximum grade encountered on a given section of track and may be the actual grade, where such is of long extent, or the virtual grade, where the inertia of the train may be used to advantage in overcoming a heavier short grade. The ruling grade of freight hauling roads should be limited to 2 per cent. or less when the topography of the country will permit, in fact, on a modern freight road any grade exceeding 1 per cent. maximum would be considered excessive, and would demand the use of helper locomotives. While low grades are not so important on electric suburban railways where the income is largely derived from passenger receipts, the future possibilities of freight traffic over these lines makes a low gradient desirable whenever possible.

26. Coefficient of adhesion expresses the ratio between total tractive effort and weight on drivers. Coefficient $= F_e / W$ where F_e is the maximum possible tractive effort in lb., and W is the weight on the drivers in lb.

This is expressed in per cent. and is a variable depending upon the condition of track and composition of wheel. See Par. 27.

It is good practice to design the motive power of a car or locomotive so that it can slip the wheels on a dry rail, this practice not being strictly followed in very high-speed motor-car equipment, owing to the enormous current input that this would demand of such an equipment, designed primarily for low tractive effort and high speed. In steam locomotive practice, however, it is customary to rate the locomotive at the tractive effort corresponding to a coefficient of 22 per cent. of the weight upon the drivers, that is, at practically the slipping point of the drivers. This practice is handed down from steam-locomotive practice, where the tractive effort is fluctuating during one revolution of the driver, hence on account of the perfectly uniform torque exerted by the electric motor, the electric locomotive could readily be rated about 15 per cent. higher in tractive effort for the same weight upon the drivers.

27. Coefficients of adhesion with uniform torque (approx.)

Clean dry rail	30 per cent.
Wet rail	18 per cent. with sand 22 per cent.
Rail covered with sleet	15 per cent. with sand 20 per cent.
Rail covered with dry snow	10 per cent. with sand 15 per cent.

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In using these figures allowance must be made for unequal distribution of weight on drivers due to weight transfer from pull on drawbar or truck centre pin. The minimum driver weight must be used unless drivers are connected by side rods.

28. Maximum allowable grades. The values for coefficients of adhesion given in Par. **27** are based upon the assumption that the motive power gives a perfectly uniform torque. Thus, while 30 per cent. is the maximum value given, tests with electric locomotives have recorded as high a coefficient as 35 to 40 per cent. under very favorable conditions. For single motor-car service where all axles are equipped with motors, the tractive effort available with a coefficient of adhesion of 22 per cent. is 22 per cent of 2,000 = 440 lb. per ton, or sufficient to carry the car up a 22 per cent. grade, taking no account of train resistance or reduced effective weight of car on such an extreme grade, Par. **26**. A motor car, however, has to operate under all climatic conditions, and hence is liable to meet conditions where the coefficient of adhesion may drop to as low as 10 per cent., so that the maximum grade in practice should never exceed 12 to 13 per cent. Should such extreme grades be necessary, some form of **track brake** should be provided as an auxiliary to hand or air brakes in order to ensure safety in operation. Moreover, all curves encountered should be compensated where grades are heavy, especially if the rigid wheel base of the trucks is large and the radius of curvature small.

29. Determination of locomotive tonnage rating. In determining the tonnage rating for any locomotive in a given service usually two methods are employed, one for light grades and level track and the other for heavy grades. On *level track* and *light grades* it is usual to allow 6 lb. per ton for train resistance, 10 to 20 lb. for acceleration and 25 per cent. coefficient of adhesion for the slipping point of the wheel. Thus when the train is up to speed the tractive effort required to keep the train running is approximately only 6 to 10 per cent. of the weight on the drivers. On the other hand if this rule is used for determining the tonnage rating on a *heavy grade*, say 2 per cent., the train resistance will be 6 lb. for resistance, 30 lb. for grade and 10 lb. for acceleration making a total of 56 lb. per ton at starting and 46 lb. per ton running, or when the train is up to speed the tractive effort required is $^{46}/_{2240} \times 25 = 20.5$ per cent. of the weight on drivers. For satisfactory practical operation it has been found that the tractive effort required to keep a train running on ruling grades shoulb not exceed about 18 per cent. and for this reason electric locomotives in freight service are given a tonnage rating equivalent to a tractive effort of about 18 per cent. of the weight on drivers, and on light grades and in passenger service a somewhat less percentage of the weight on drivers is taken depending upon the speed required.

SPEED-TIME CURVES AND MOTOR CHARACTERISTICS

30. Acceleration. The many problems connected with train acceleration can be treated either analytically or graphically. As will be shown later, there are so many variables entering into the consideration of train movements at variable speeds that the analytical method becomes somewhat complicated and difficult to follow. The graphical method is equally as accurate, much easier to work with, and the final results are given in such form that they are of general application without calling for the familiarity of terms and symbols made necessary by the analytical treatment.

There are several terms used in connection with train acceleration phenomena which are defined in Par. **31** to **37**.

31. Tractive effort is the torque in pounds developed at the rim of the wheels.

32. Braking effort, also expressed in pounds is the opposite of tractive effort, expresses the force tending to retard the motion of the train and bring it to rest.

33. Rate of acceleration is the rate of increase in speed of train, and may be expressed in feet per sec. per sec., or miles per hr. per sec.—usually the latter.

34. Rate of braking is the rate of decrease in speed of train. Both rate of acceleration and rate of braking may vary considerably during successive periods of time, depending upon type of motive power and brake rigging used.

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35. Train resistance a variable, expressed in pounds per ton and tending retard the motion of the train (Par. **4** to **29**).

36. Speed-time curves show the relation of the above variables in rve form, generally with speed in miles per hr. as ordinates, and elapsed ne in seconds as abscissas.

37. Energy curves show the energy consumption, generally expressed watt-hours per ton mile, for different rates of acceleration,* braking and ain resistance, for various elapsed times over a given distance run.

38. Curves of free acceleration. A better understanding of the possible ovements of a car or train operating at different speeds over different stances, is obtained by eliminating the type of motive wer and brake rigging used, d assuming straight-line acerating, coasting and brakg curves. The results so tained are fundamental, and ay be applied to examples, nsidering any type of motive wer using a correction fac-r, which will be treated later, own as the efficiency of acleration.

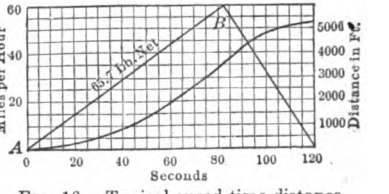
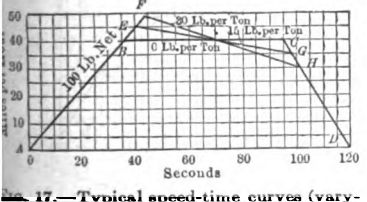


FIG. 16.—Typical speed-time-distance curve (no coasting).

39. The problem of train cceleration deals with the ovement of a given weight rer a given distance within a specified time. As it is impracticable to art and stop the train instantaneously, it is necessary to deal with some nite rate of acceleration and braking, thus giving rise to the simple form f speed-time curves shown in Fig. 16. The speed-time curve is here own in the simplest form, acceleration being carried on at constant rate p to the point of applying brakes, which are so applied as to also give a nstant rate of braking. The area enclosed within the triangle, A, B, C, is proportional to the distance travelled, the distance covered up to any instant being represented by the distance-time curve shown. Thus, with the constants chosen in Fig. 16, a maximum speed of 60 miles per hr. is required to obtain an average speed of 30 miles per hr., that is, covering a distance of 5,280 ft. in 120 sec.



—17.—Typical speed-time curves (varying coasting resistance).

40. The simple formulas required in the construction of fundamental speed-time curves are given as follows:

Let v represent velocity in ft. per sec.; S, velocity in miles per hour; f, the orce producing acceleration expressed in lb.; t, the time interval expressed n sec.; m, the mass, $m = w/g = w/32.2$; w, the weight in lb.

Then,

$$f = \frac{mv}{t} = \frac{wv}{gt} \text{ lb.} \tag{7}$$

On the basis of one ton,

$$f = \frac{2{,}000v}{32.2t} \text{ lb. per ton} \tag{8}$$

It is more convenient to express velocity in miles per hr.

Hence $$f = \frac{2{,}000 \times 5{,}280 \times S}{32.2 \times 60 \times 60 \times t} = 91.2\frac{S}{t} \text{ lb. per ton} \tag{9}$$

or if S is 1 mile per hour and t is 1 second

$$f = 91.2 \text{ lb. per ton}$$

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The velocity in miles per hour,

$$S = 0.01098 \text{ ft.},$$

f being expressed in lb. per ton.

The distance covered in any given time may be expressed

$$L = \frac{f t^2}{2m} \times \frac{f t^2 \times 32.2}{2 \times 2{,}000} = 0.00804 f t^2 \quad \text{(ft. per ton)} \quad (10$$

(See Par. 60)

41. Actual speed-time curves. In practical operation it is not possibl to choose the rate of acceleration and braking with such niceness as shown i Fig. 16, a greater or less period of coasting being required. Introducin coasting gives rise to the form of speed-time curve shown in Fig. 17, showin three friction rates—$f = 0$, 15 lb. per ton, and 30 lb. per ton respectively With no friction the speed-time curve, A, B, C, D, is constructed, the spee being maintained constant at 40 miles per hr. during the coasting period With 15 lb. per ton friction, the speed-time curve, A, E, G, D, is formed, an with 30 lb. per ton friction the speed-time curve, A, F, H, D. The intro duction of friction occasions a falling off of speed during the coasting perio proportional to the friction value taken, which for the sake of simplicit is here assumed to be constant at all speeds.

The speed-time curves shown in Figs. 16 and 17 both indicate the comple tion of the run of 5,280 ft. in 120 sec., although in one case the rate of acceler tion was that produced by 65.7 lb. per ton, and in the other case by 100 lb per ton. These curves are of equal area, as the distance in each case i 5,280 ft. Thus, it becomes possible to produce any number of speed-tim curves, for a given distance and elapsed time, by varying the rate of accelera tion with consequent variation in time of coasting.

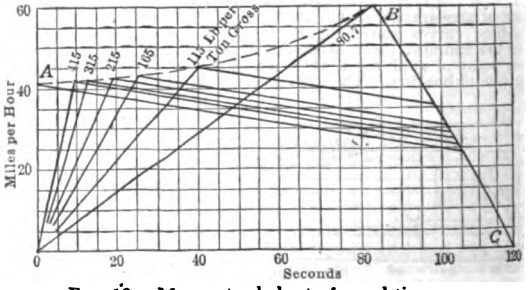


FIG. 18.—More extended set of speed-time curves.

A more extended set of curves is given in Fig. 18, for the same distance o 1 mile covered in 120 sec., the rate of acceleration varying from 0.713 miles per hr. per sec. as a minimum to an infinite number of miles per hr. per sec as a maximum.

A train resistance value of 15 lb. per ton is assumed constant at all speeds and the dotted curve, A, B, is described by the loci of the maximum speeds reached with the different rates of acceleration. The highest maximum speed required is obtained with no coasting, and the minimum speed is obtained with an infinite rate of acceleration. The pounds per ton corresponding to the different accelerating rates are given as including 15 lb. per ton train resistance, hence the net tractive effort values corresponding to the rates of acceleration indicated are 15 lb. per ton less than the figures given.

42. Application of unit-distance speed-time curves. Instead of plotting similar curves for distances other than 5,280 ft., advantage may be taken of the fact that the area enclosed by the speed-time curve is proportional to the distance travelled and the coordinates are proportional to the square root of the enclosed area. It is convenient, therefore, to plot a full series of curves for one distance, preferably one stop per mile, that is, a dis-

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tance of 5,280 ft. run, and to apply the results so obtained for any other distance by using a factor expressing the relation of the square roots of the distance travelled. This is shown in Fig. 19, where *A*, *B*, *C*, *D*, represents an area of 1 mile, or one stop per mile, *A*, *F*, *I*, *L*, two stops per mile with a factor of $1/\sqrt{2}=0.707$; *A*, *E*, *H*, *K*, four stops per mile with a factor of $1/\sqrt{4}=0.5$, and *A*, *G*, *J*, *M*, one stop in 1½ miles with a factor of $\sqrt{1.5}=1.225$.

Referring to Fig. 17, it is obvious that a similar sheet could be prepared for any elapsed time other than 120 sec., using the same train resistance and braking values of 15 and 150 lb. per ton respectively.

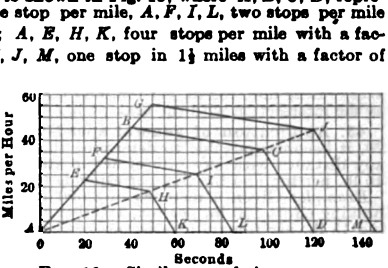


FIG. 19.—Similar speed-time curves (varying) distances.

43. Imposed time limits. In Fig. 20 is shown the time limits imposed by 15 lb. per ton train resistance, and 150 lb. per ton braking for any length of run and any rate of acceleration. The dotted curves indicate the loci of the several maximum speeds reached with different accelerating rates for a run made in a given elapsed time. Thus the dotted curve terminating at 80.7 lb. per ton is a reproduction of the similar dotted curve, *A*, *B*, given in Fig. 20, and gives the maximum speed reached with any rate of acceleration for a run of

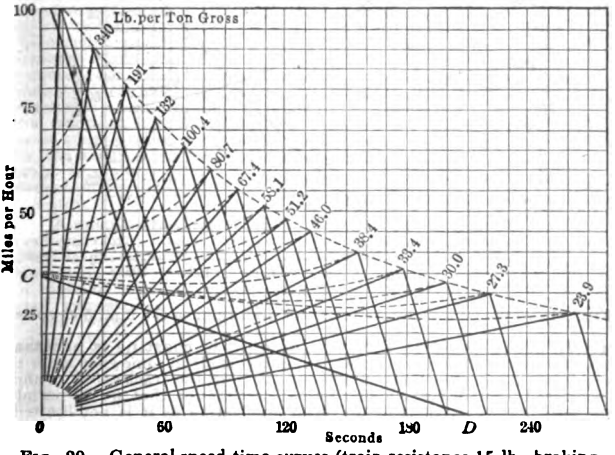


FIG. 20.—General speed-time curves (train-resistance 15 lb., braking 150 lb.).

5,280 ft. in 120 sec. with 15 lb. per ton train resistance and 150 lb. braking effort. Similarly, the dotted curve terminating at 100.4 lb. per ton gives the limiting maximum speeds reached, with any rate of acceleration, when a run of 5,280 ft. is accomplished in 110 sec., using the same values of train resistance, braking, etc.

44. Time limits with and without coasting. The full line *C*, *D*, gives the angle made by a coasting line when the rate train friction is 15 lb. per ton.

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Thus, in a run completed in 120 sec., the minimum accelerating rate corresponds to 80.7 lb. per ton (gross), with no coasting introduced, for here braking commences as soon as acceleration ceases.

If a higher rate of acceleration than 80.7 lb. per ton be used for a cycle completed in 120 sec., for example 132 lb. per ton (gross), coasting must be introduced between the accelerating and braking lines. This coasting line may be plotted, with 132 lb. per ton acceleration, by drawing a line parallel to full line C,D (Fig. 20). This line starts at the intersection of accelerating line, 132 lb. per ton, and the dotted line to 80.7; and terminates at the intersection with the braking line ending at 120 sec.

43. Application of general speed-time curves. By the use of Fig. 20, it becomes possible to determine the time required to make a run over any distance with any rate of acceleration, provided the train resistance is 15 lb. per ton and braking corresponds to 150 lb. per ton retarding effort.

Example: Given a distance of 8,000 ft., train resistance 15 lb. per ton, braking effort 150 lb. per ton, tractive effort gross 67.4 lb. per ton (including 15 lb. per ton train resistance), what is the minimum time required to perform the run and what maximum speed is reached?

Solution: From Fig. 20, minimum elapsed time with 67.4 lb. tractive effort is 130 sec. with no coasting. Ratio of distances $= \sqrt{8{,}000/5{,}280} = 1.23$. Hence for 8,000 ft. time of run $= 130 \times 1.23 = 160$ sec.; maximum speed for 5,280 ft. $= 55.6$ miles per hr.; hence for 8,000 ft., speed $= 55.6 \times 1.23 = 68.5$ miles per hr.

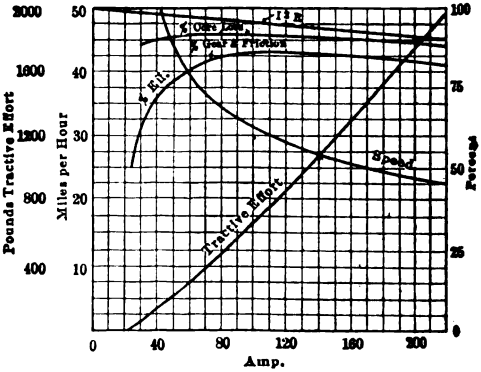


FIG. 21.—Typical direct-current motor performance (75 h.p., 500 volts).

46. In actual practice, a certain amount of coasting is necessary; hence, the run of 8,000 ft. (Par. 45), would be made in somewhat more than the minimum possible limit of 160 sec., or else the tractive effort should be increased to allow for a higher rate of acceleration that would permit of some coasting. Fig. 20 is of universal application as it is not limited to any particular type of motive power, having its own peculiar speed characteristics. Moreover, the values of 15 lb. and 150 lb. chosen for train resistance and braking effort respectively are conservative operating values obtaining in practice.

47. The maximum speed reached during the performance of a service run will be little influenced by the type of motive power and its curve characteristics (See Par. 41). The values indicated in Fig. 20 will hold approximately true in service operation with series motors of either the alternating-current or direct-current types, and hence, the curves given constitute a set of fundamental data by means of which it becomes possible to attack any acceleration problem and determine the data required.

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48. Electric motors used in railway service are of the following types:

(1) Series-wound direct-current motors,
(2) Single-phase alternating-current motors,
(3) Polyphase alternating-current induction motors.

In addition to the above, there have been several attempts at operating shunt-wound direct-current motors, but as such motors have not come into even partial use, owing to the superior qualities of other types, the shunt-wound motor will not be discussed.

49. Direct-current series-wound motor characteristics and applications. The direct-current series motor has the general characteristics

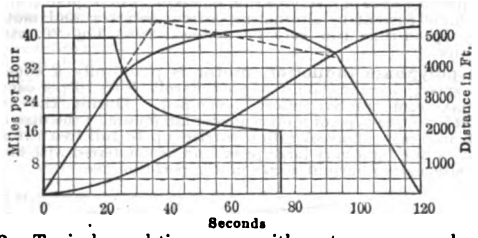


FIG. 22.—Typical speed-time curve with motor-curve acceleration.

shown in Fig. 21. Applying this motor characteristic to the performance of a car, it becomes necessary to reduce the motor voltage during the starting or accelerating period of the car in order to limit the tractive effort to a value that will not slip the driving wheels. In other words, if full voltage were to be applied to the motor at standstill, the resulting current would be enormous, would produce a torque that would slip the wheels, and would far exceed the safe commutating capacity of the motor. Hence, the necessity of introducing external starting resistance in successive steps during acceleration, with the result that the starting current is maintained practically constant at the full-load rating of the motor.

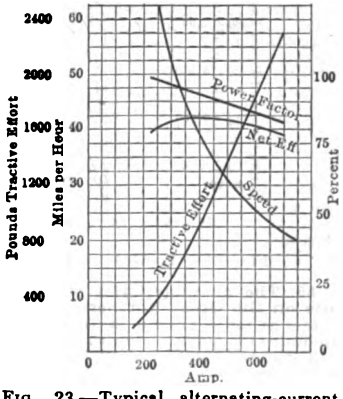


FIG. 23.—Typical alternating-current motor performance (75 h.p., 225 volts).

50. A speed-time curve with direct-current series-wound motor is shown in Fig. 22, indicating a constant current input up to a speed of 28 miles per hr. At higher values of speed, the motor has full voltage applied to its brushes, and hence operates with a constantly decreasing current until full speed is reached, when current and tractive effort both become constant.

51. Advantage of straight-line functions. As many acceleration problems involve curves of rather short radii and grades, requiring a step-by-step method of plotting the performance of a train (Fig. 20), operation, any general speed-time curves other than straight line functions would not be of universal application; especially as considerable variation exists in the characteristics of railway motors in general use. The straight-line functions give sufficiently close approximation as regards maximum speed, rate of acceleration and general constants required to perform a given schedule as indicated in Fig. 22, comparison of straight line and motor characteristics.

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52. The alternating-current series-wound motor must operate at a lower flux density than its direct-current competitor and hence has a motor characteristic that is even more drooping than that of the direct-current series-wound motor. In consequence, there is less straight-line operation and more motor-curve operation during the accelerating period, resulting in a lesser peak-load demand upon the distributing system. Thus, while constant rate of acceleration with direct-current motors may be carried up to 80 per cent. of the free running speed, this ratio may be reduced to possibly 40 per cent. with the alternating-current motor.

53. Speed with series-wound motors. The maximum speed attained during the performance of a service run, however, will be practically the same for either direct-current or alternating-current series-wound motors, and a preliminary speed-time run may be deduced from Fig. 20, straight line characteristics.

54. The polyphase induction motor is practically a constant-speed motor, its speed dropping only approximately 5 to 10 per cent. from no load to maximum tractive effort developed. During the accelerating period, therefore, this type of motive power labors under the disadvantage of demanding full rate of acceleration carried up to full free running speed, a condition calling for a very large peak load as compared with either direct-current or alternating-current series motor performance.

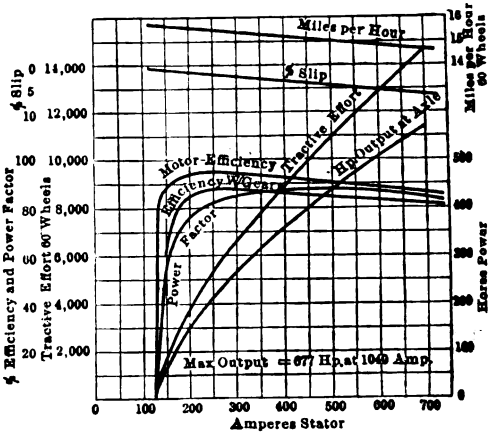


FIG. 24.—Typical polyphase induction motor performance.

55. The characteristics of the three-phase induction motors in use on the Great Northern locomotives are shown in Fig. 24. This motor is rated 475 h.p. at 75 deg. cent. rise for 1 hr., and the speed curve indicates the almost constant speed at which such equipments must operate.

For starting and for fractional speed running, a resistor is inserted in series in the secondary circuit, the speed attained being zero when the full secondary e.m.f. is absorbed by the combined armature and external resistance.

Owing to its general unfitness for rapid-transit service with frequent stops the induction motor is limited to long distance running as its legitimate field.

56. The permissible rate of acceleration is determined first by comfort of passengers and second by the tractive effort available. It has been found experimentally that the discomfort to passengers is occasioned largely by the change in rate of acceleration and not entirely upon its intensity. Thus, a very high rate, 2 miles per hr. per sec. may occasion no discom-

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fort with cars having cross seats, provided the rate of acceleration is attained gradually with no abrupt change. The following accelerating rates obtain in practical operation.

57. Table of accelerating rates

Locomotives	
Steam locomotives, freight service	0.1 to 0.2 miles per hr. per sec.
Steam locomotives, passenger service	0.2 to 0.5 miles per hr. per sec.
Electric locomotives, passenger service	0.3 to 0.6 miles per hr. per sec.
Motor Cars	
Electric motor cars interurban service	0.8 to 1.3 miles per hr. per sec.
Electric motor cars city service	1.3 to 1.8 miles per hr. per sec.
Electric motor cars rapid transit service	1.5 to 2.00 miles per hr. per sec.
Highest practical rate	2.00 to 2.5 miles per hr. per sec.

58. Limits of acceleration rate. The rates given in Par. 57 apply only to that part of the accelerating period during which the current is maintained practically constant by means of cutting out successive sections of the external starting resistance. The higher rates from 1.0 to 2.5 miles per hr. per sec. demand a gradual increase to those values in order to avoid the discomfort to passengers that would surely result from a sudden application or cessation of such rates.

The coefficient of adhesion (Par. 26) also determines the accelerating rate by limiting the available tractive effort, thus giving rise to the values given above for locomotive practice. As the practice is common to run locomotives very close to the limit of adhesion for full-speed operation on grades, it leaves but a small excess of tractive effort available to accelerate the train. High acceleration demands that all axles shall be equipped with motors, and if trains are run, that all cars must be motor cars, that is, no trailers are permissible when extreme accelerating rates are required to make the schedule desired.

59. Limits of braking rate. The limits reached in acceleration hold equally true in braking. As a matter of fact, acceleration may be at a higher rate than braking, for two reasons: first, discomfort to passengers is greater during braking of cross-seat cars, as the inertia of the passenger tends to carry him away from his seat and he lacks the supporting back that prevents discomfort during rapid acceleration when his body is pressed backward; second, in braking a train to standstill, it is necessary for the operator to stop within a distance of a few feet of a fixed spot, and the skill shown in judging speed and distance will determine the braking rate. During acceleration no such limit exists; the motorman has absolute freedom. There is, however, a system of motor control available that will bring about uniform or automatic acceleration, the rate being determined by the necessities of the service.

60. The inertia effect of revolving parts must be considered. This factor reduces the effective accelerating and braking rates. In other words, it is necessary to expend from 4 to 12 per cent. more tractive effort during acceleration and braking in order to overcome the inertia of car wheels, gears and motor armatures, than is required to accelerate the car or train longitudinally on a level track. This inertia may be calculated as follows:

The energy of a rotating body $= W + gV^2 = W + g\frac{r^2}{R^2}V^2$ (ft-lb.) (11)

where V = speed of the centre of gravity of the body in ft. per sec.
V = speed of train in ft. per sec.
r = radius of gyration in ft.
R = radius of rim in ft.

or the effective weight $= Wr^2/R^2$. The ratio r^2/R^2 has been found from a large number of tests to be approximately 0.6 for ordinary designs of car wheels, hence the effective weight of the wheels

$= 0.6 \times$ weight of wheels (lb.) (12)

The ratio, r^2/R^2, for armature is approximately 0.5. For geared motors it is important that allowance be made for the higher speed of the armature.

Hence the effective weight of the armature $= 0.5 \left(\frac{\text{dia. of arm}}{\text{dia. of wheel}} \times \text{gear ratio}\right)^2 \times$ weight of armature (lb.) (13)

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It is common practice to use 100 lb. per ton instead of 91.2 lb. per ton for 1 mile per hr. per sec. acceleration, and take dead weight of train only. This allows for approximately 10 per cent. equivalent weight due to the inertia of rotating parts. It is a very simple method and its results are very near the proper amount for street cars. For more accurate calculations, see Par. 61.

61. Per cent. of total tractive effort consumed in rotating parts

Electric locomotive and heavy freight train	5 per cent.
Electric locomotive and high-speed passenger trains	7 per cent.
Electric high-speed motor cars	7 per cent.
Low-speed motor cars	10 per cent.

The above percentages added to 91.2 and multiplied by the rate of acceleration will give the total pounds tractive effort per ton required for acceleration.

62. Calculation of acceleration rate. In figuring upon accelerating and braking problems for different classes of service, the percentages in Par. 61 should be added to the actual train weight to obtain the effective train weight. The net tractive effort as determined by the gross tractive effort minus the train resistance can then be used in connection with the effective train weight to arrive at the rate of acceleration as expressed in miles per hr. per sec.

63. Schedule speed, expressed in miles per hr., denotes the average speed of a train including all stops, slow downs, etc., being the distance run in miles divided by the elapsed time in hours, including time of stops enroute. See Par. 64.

64. Duration of service stops

Through trains, steam	5 min.
Local trains, steam	2 min.
Interurban cars, electric	10 to 30 sec.
City rapid transit trains, electric	10 to 20 sec.
City surface cars, electric	5 to 12 sec.

The following frequency of stops are characteristic of the different classes of railway service:

65. Frequency of stops in service

Steam locomotive through service	1 stop in 100 miles.
Steam locomotive local service	1 stop in 20 miles.
Steam locomotive suburban service	1 stop per mile.
Electric interurban express	1 stop in 10 miles.
Electric interurban local	1 stop in 2 miles.
Electric suburban	1 to 2 stops per mile.
City elevated or rapid transit	2 to 3 stops per mile
City surface lines	5 to 10 stops per mile.

66. The relation between schedule and maximum speed with varying frequency of stops is expressed in Fig. 26, which indicates the schedule speed possible to make with trains having a free running speed of 30, 45, 60 and 75 miles per hr. respectively.

Thus with a train geared for a free running speed of 60 miles per hr. it is possible to make a schedule of 45.5 miles per hr. with one stop in four miles, 37.5 miles per hr. with one stop in 2 miles, etc.

For frequent-stop service, a low free-running speed is desirable as it is easier on the equipment, calls for less motor capacity and less energy consumed in performing the service. Hence, it is advisable to use the lowest maximum speed that will give the schedule desired.

67. Effect of acceleration on frequent-stop service. When using Fig. 26, it should be recognized that where stops are more frequent than one per mile, the rate of acceleration becomes a controlling factor, and as shown in the curve, when the frequency of stops approaches three or more per mile, the maximum free-running speed of the equipment does not have any appreciable effect upon the possible schedule speed. Hence, for frequent stop service where it is of great importance to attain the highest possible schedule speed, recourse should be had to Fig. 20, in order to determine the advantages of higher rates of acceleration than the 120 lb. gross which forms the basis of Fig. 25.

68. Effect of track curves on rapid service. In all classes of service, due recognition should be paid to the effect of curves of such short radii as to

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demand slowing down while rounding them. The safe speed at which a curve may be taken will depend upon the elevation of the outer rail, but a greater elevation than 8 in. is not common. Also curves having a spiral approach will ride much easier than those in which the tangent leads directly into the curve.

69. Safe maximum speed on track curves

Radius of curve, ft.....	10,000	5,000	2,000	1,000	500	200	100	50
Speed, miles per hr.....	100	75	50	35	25	15	10	6

The above values apply only when full elevation may be given outer rail. Speeds will be less when operating in city streets where such elevation is not possible, and where wheel flanges of three-quarters of an inch or less are the rule.

70. Limitations of theoretical schedules. On any road abounding in curves of short radius, it will not be possible to reach the schedules given in Fig. 25. No general rule can be given to fit all cases, as each problem must be treated according to local conditions. There is sufficient leeway in the schedules given in Fig. 25 to allow for irregularities of stops, as there is included a period of 10 sec. coasting that may be cut out when a stop has

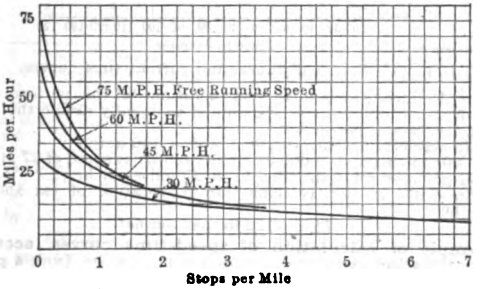


FIG. 25.—Relation between maximum and schedule speed and stops per mile.

exceeded the limit of 15 sec. assumed, but excessive duration of stops and time lost in meeting and passing trains on single-track systems, is not allowed for.

71. The method of plotting speed-time relations consists in taking successive small intervals of time or speed and assuming that the accelerating force, train resistance and other factors remain constant during the interval. It is, therefore, only necessary to take sufficiently small intervals in order that the so-called step-by-step method may give results of great accuracy. Any speed-time calculations are at best an approximation, owing to the fact that in actual train operation there is a constant change taking place in the fundamental factors assumed as the basis of calculations. Hence a fair degree of accuracy is sufficient to afford as close an approximation as the problem warrants. This does not mean that errors made in calculations are of no consequence, but that it is not required to assume extremely small speed intervals in order that the resulting speed-time values shall bear a proper relation.

72. Speed-time curves following motor characteristics. As the characteristics of different motors vary somewhat from each other, and there is considerable divergence between the characteristics of motors of different types, it is best to plot speed-time curves from the characteristics of the motor to be used in a given proposed service. Even this is a refinement not necessary in many problems of a more general character, as it will be found that the speed and torque curves of modern railway motors are of the same general shape and may in fact be expressed by a simple formula.

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73. Example of calculation of speed-time curves;* **tractive force.** The best step-by-step method of plotting curves consists in assuming small speed increments, two-mile increments giving sufficient accuracy in practically all cases.

Example: Given a car weighing 32 tons, with an equipment of 4 motors. Motor characteristics as per Fig. 21. Average line voltage 500. Find the relation of speed, amperes, distance and time for normal acceleration within the capacity of the motors.

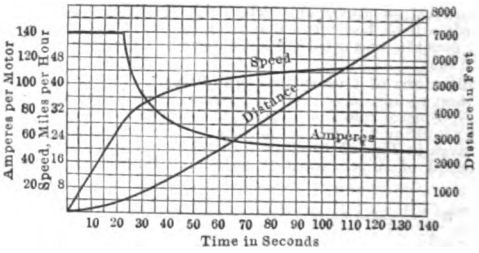


FIG. 26.—Speed, distance, and current time curves.

Solution: Reduce problem to consideration of the performance of a single motor as all motors may be assumed to equally divide the work.
Hence, 32/4 = 8 tons per motor.
Assume safe accelerating current per motor = 140 amp.
From (Fig. 20) 140 amp. = 1,090 lb. tractive effort at speed of 27 miles per hr.
Car friction per motor 116 lb. (Fig. 9) at 27 miles per hr.
1,090 − 116 = 974 lb. net available for acceleration of car and rotating parts (Par. **60**).

$$974/8 = 122 \text{ lb. per ton net.}$$

74. Example of calculation of speed-time curves, acceleration. To find **acceleration** expressed in miles per hr. per sec. from a given force expressed in lb. per ton, proceed as follows.

Acceleration, expressed in miles per hr. per sec. = $[(32.2 \times 0.682)/2{,}000] \times$ lb. per ton = (lb. per ton)/91.2. The above value of (lb. per ton)/91.2 applies only to the net lb. per ton available for car acceleration only. In this particular problem assume 7 per cent. of the accelerating tractive force as being required to overcome the inertia of the rotating parts, then the factor of acceleration expressed in miles per hr. per sec. = (net lb. per ton)/(91.2×1.07) = (lb. per ton)/97.5. Hence—acceleration = 122/97.5 = 1.25 miles per hr. per sec.

Assume that car resistance remains constant at all speeds up to 27 miles per hr., as error introduced thereby is so small as to make it unnecessary to plot the curve step by step until motor-curve running is reached at 27 miles per hr.

The several relations may be calculated as given in Par. **76.**

75. Example of calculation of speed-time curves; effects of track curves, grades and coasting. The above example is worked out on basis of level tangent track. The calculation of speed-time curves is generally based upon this assumption. Where it is necessary to predetermine the performance of a motor operating over grades and around curves, add or deduct tractive force so consumed from gross tractive effort and proceed as in Par. **76.** Also see Par. **22** and **23.**

Completing the speed-time cycle by introducing coasting and braking requires the same treatment as in Par. **76** except that both coasting and braking are equivalent to negative acceleration. Another method of plotting

* For other methods of plotting speed-time curves see Mailloux, C. O. "Notes on the Plotting of Speed-time Curves," *Proc.* Am. Inst. of Elec. Eng., 1902, Vol. XIX, p. 901. E. C. Woodruff, *Trans.* Am. Inst. of Elec. Eng., 1914, Vol. XXXIII, p. 1673 and Discussion.

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speed-time curves is given by Mailloux in Proceedings American Institute of Electrical Engineers, June, 1902.

76. Relation of speed, distance, amperes and time (Par. 73); example of detailed calculations

1	2	3	4	5	6	7	8	9	10	11
	27	1,090	116	974	1.25	21.6	21.6	428	428	140
2	29	980	119	861	1.10	1.82	23.4	75	503	130
2	31	790	126	664	0.85	2.25	25.6	99	602	112
2	33	640	133	507	0.65	3.08	28.7	145	747	97
2	35	540	140	400	0.51	3.92	32.6	196	943	86
2	37	440	147	293	0.37	5.40	38.0	286	1,229	76
2	39	370	155	215	0.28	7.15	45.2	410	1,639	68
2	41	310	163	147	0.19	10.5	55.7	633	2,272	61
2	43	270	172	98	0.13	15.4	71.1	952	3,234	57
2	45	230	180	50	0.06	34.4	105.0	2,230	5,464	52

NOTE.—1. Speed increment of 2 miles per hr. 2. Sum of speed increments. 3. Gross tractive effort as obtained from motor characteristics (Fig. 22). 4. Car friction per motor (Fig. 9). 5. Net tractive effort available for gross acceleration after deducting car friction. 6. Acceleration as obtained by dividing net accelerating force (column 5 reduced to lb. per ton) by acceleration factor as determined (97.5). 7. Time increment as determined from 1 and 6. 8. Total elapsed time summation of 7. 9. Distance increment as determined from 2 and 7. 10. Total distance traveled, summation of 9. 11. Amperes as determined from motor characteristics. Values in 3, 5, 6 are average values obtaining during increase of speed increment in 1.

ENERGY AND POWER CONSUMPTION

77. The energy consumed in moving a train at constant speed is expended in overcoming train resistance (Figs. 9 to 14 inclusive) and internal motor losses. It is customary for manufacturers to give the net efficiency of railway motors after having carefully determined their internal losses from stand tests, and hence, the railway operator is concerned only with the determination of the energy required to overcome train resistance when the speed of the train is constant at any fixed miles per hr.

Curves given in Figs. 9 to 14 inclusive express in pounds per ton the train resistance of different weights and combinations of cars. As a ready means of changing from pounds per ton train resistance to watt-hours per ton-mile, the following holds approximately true: Pounds per ton × 2 = watt-hours per ton-mile.

The above gives the watt-hours per ton-mile net output of the motive power, and to get train kilowatts input it is necessary to know the efficiency obtaining for different sizes of equipments as given by the manufacturers.

78. Efficiency of direct-current railway motors

Capacity, h.p.	40	60	80	100	125	150	200	250	*250	*500	700.0
Max. Efficiency, per cent.	84	86	87	88	89	89	89	89	91	93	90.5
Efficiency Car, full speed, per cent.	68	70	72	73	74	74	75	75	90	92	78.0

79. The maximum efficiency of railway motors of the geared type occurs during maximum output, hence the values quoted should be used for calculation of the power required to accelerate a car or train. An exception to this rule may be taken in locomotive work, where it is customary to force the motors to nearly their maximum rated output even after the train has reached its normal maximum speed.

* Motors of gearless type

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80. The efficiency when the car is at full speed is generally lower with motors of the geared type, owing largely to the losses in gears and also in the magnetic circuit of the motors themselves. This lower efficiency at higher speeds does not hold true of motors of the gearless type as indicated in Par. 78. The advantage of using gearless motors for high-speed passenger service is clearly indicated by the extremely high efficiency at light outputs. On the other hand, such motors do not compare favorably with the geared type for heavy freight haulage as the efficiency falls off rapidly at the overloads characteristic of this class of service.

81. Power requirements at constant speed. To determine power required to propel a car or train at any constant speed, proceed as follows:

$$P = \frac{F \times 2 \times W \times S}{\eta \times 1{,}000} \quad \text{(kw.)} \qquad (14)$$

wherein F is the train resistance in lb. per ton (from Figs. 9 to 14 inclusive); W the weight of the car or train in tons; S the speed of the train in miles per hr., and η the motor efficiency with the train at full speed.

82. Calculation of power requirements of motor-car trains. The tables show the kilowatts input required for motor-car trains, and also for high-speed passenger-train and low-speed freight-train operation. These tables are based directly upon the train-resistance values given in Figs. 9 to 14 inclusive, and represent the kilowatts input that would be expected with well-ballasted rail when trains are running at constant speed.

Constants assumed in these calculations are: efficiency at full speed, 75 per cent. based upon the use of direct-current geared motors; and train resistance as obtained from the formula

$$\text{Tractive effort} = \frac{50}{\sqrt{W}} + 0.03\,S + \frac{0.002aS^2}{W}\left(1 + \frac{n-1}{10}\right) \quad \text{(lb. per ton)} \qquad (15)$$

Cross-sectional area of cars is as follows: 20-ton car, cross-section, 90 sq. ft.; 30-ton car, cross-section, 100 sq. ft.; 40-ton car, cross-section, 110 sq. ft.; 50-ton car, cross-section, 120 sq. ft.; 60-ton car cross-section, 130 sq. ft.

83. Train input for constant-speed running on level tangent track, motor-car service

(Input values expressed in kilowatts)

Train weight	Speed (miles per hr.)									
	10	20	30	40	50	60	70	80	90	100
2–20 ton cars	9.3	22.4	42.5	72.5	116.0	...	...	...	...	...
2–30 ton cars	11.5	27.4	51.4	87.0	137.0	206	...	...	...	...
2–40 ton cars	13.2	31.6	59.0	99.3	156.0	234	336	...	...	...
2–50 ton cars	14.8	35.5	66.3	111.0	175.0	261	374	520	699	...
2–60 ton cars	16.3	38.8	71.7	119.0	185.0	274	390	540	720	945
20 ton car	6.5	16.2	32.0	56.7	93.5	...	...	...	...	...
30 ton car	8.0	19.5	38.4	67.3	109.0	167	...	...	...	...
40 ton car	9.4	23.1	44.1	76.2	124.0	188	276	...	...	...
50 ton car	10.4	25.6	49.2	84.8	137.0	210	305	430	584	...
60 ton car	11.5	27.9	52.8	90.2	144.0	218	316	442	599	792
3–20 ton cars	11.4	27.2	50.9	84.1	136.0	...	...	...	...	...
3–30 ton cars	14.0	33.3	61.8	103.0	162.0	240	...	...	...	...
3–40 ton cars	16.3	38.7	71.5	119.0	185.0	271	391	...	...	...
3–50 ton cars	18.4	43.7	80.6	134.0	206.0	308	437	602	805	...
3–60 ton cars	20.1	48.0	87.4	144.0	222.0	326	460	635	925	1,092
5–20 ton cars	14.8	35.3	65.4	109.0	171.0	...	...	...	...	...
5–30 ton cars	18.3	43.5	80.0	133.0	205.0	303	...	...	...	...
5–40 ton cars	21.3	50.8	93.2	154.0	237.0	348	493	...	...	...
5–50 ton cars	26.2	61.9	112.0	183.0	279.0	406	568	773	1,026	...
5–60 ton cars	31.3	72.8	130.0	208.0	312.0	448	622	835	1,100	1,415

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84. Train input for constant-speed running on level tangent track, locomotive passenger service
(*Input values expressed in kilowatts*)

Gross train weight	Speed (miles per hr.)									
	10	20	30	40	50	60	70	80	90	100
200 tons.	17.5	41.2	75.8	124	196	277	398	530	710	920
300 tons.	26.1	60.5	108.0	172	258	369	511	689	905	1,160
400 tons.	32.0	79.0	139.0	219	330	462	635	840	1,100	1,405
500 tons.	41.0	99.0	170.0	268	395	563	755	995	1,295	1,645
600 tons.	50.0	118.0	203.0	315	464	645	875	1,150	1,489	1,890
700 tons.	59.0	135.0	235.0	363	530	735	996	1,305	1,682	2,132
800 tons.	69.0	154.0	267.0	410	596	828	1,117	1,460	1,878	2,375
900 tons.	77.0	173.0	300.0	459	663	920	1,238	1,615	2,070	2,620
1,000 tons.	85.0	193.0	330.0	507	730	1,011	1,358	1,771	2,261	2,860

85. Calculation of power requirements of passenger-service locomotives involve the following assumed constants: efficiency at full speed, 90 per cent. for locomotive using series-wound direct-current motors of the gearless type; cross-section of cars, 110 sq. ft.; weight of car, 50 tons; weight of track rail, not less than 80 lb. per yd.

86. Power required on grades. The values of power required to drive a car at any speed, apply only for constant speed on tangent level tracks. On up grades there is required an additional tractive effort of 20 lb. per ton for each 1 per cent. grade. Hence, to calculate power required on grades, proceed as follows:

The total train resistance is $F_0 = F + F_g$, in lb. per ton; wherein F is the train resistance in lb. per ton found from the curves, and F_g the tractive effort due to the grade (F_g = per cent. grade × 20). Then the power input is

$$P = \frac{2WF_0S}{1{,}000\eta} \qquad (16)$$

wherein W is the weight in tons of the train; F_0 the total train resistance in lb. per ton; S the speed in miles per hr., and η the efficiency of the motors.

Example: Given a train of three 40-ton cars operating up a 2 per cent. grade at 40 miles per hr. what kilowatt input is demanded by the motors?

Answer: From Fig. 11, a three-car train requires a tractive effort of 9 lb. per ton at 40 miles per hr.

To this add for grade 2 × 20 = 40 lb. per ton (see Par. 23).

Tractive effort from Fig. 11 = 9 lb.

Total tractive effort 49 lb.

Train weight = 3 × 40 = 120 tons.

Assuming that the excessive output demanded by the grade will almost completely load the motors, the maximum efficiency of the motor will be realised on the grade; with an 80-h.p. motor this would be 87 per cent.

$$\text{Hence input} = \frac{2 \times 120 \times 49 \times 40}{1{,}000 \times 0.87} = 540 \text{ kilowatts.}$$

87. Energy of acceleration. The above power values are based upon the assumption that the train has reached full speed and the power values are those required to maintain the train at constant speed. During the time that the train is attaining full speed, however, it is necessary to impart to it the energy required to accelerate the mass in the direction of travel and also to accelerate the rotating parts around their several axes.

$$\text{Energy of acceleration} = \frac{mv^2}{2} = \frac{wv^2}{2g} \quad \text{(ft-lb.)} \qquad (17)$$

where w is the weight in lb.; v the velocity in ft. per sec., and g the gravity constant (32.2 ft. per sec. per sec.).

88. Power required to overcome train resistance. In addition to the energy of acceleration, it is necessary, during the accelerating period,

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to furnish power to the train in order to overcome train resistance, a quantity constantly changing with increasing speed, and finally to supply various changing losses in the motive power and its system of control. The straight-line diagram furnishes the simplest means of attacking the speed-time problem, and it also furnishes the fundamental data for all energy-consumption curves, as it eliminates the question of motive power with its internal losses, and considers only the moving train itself.

89. The energy required to move a train from rest to a given velocity is represented by

$$W = \frac{mv^2}{2} + F_e L \qquad \text{(ft-lb.)} \qquad (18$$

wherein m is the mass; v the velocity in ft. per sec.; F_e the total train resistance in lb., and L the distance in ft. covered.

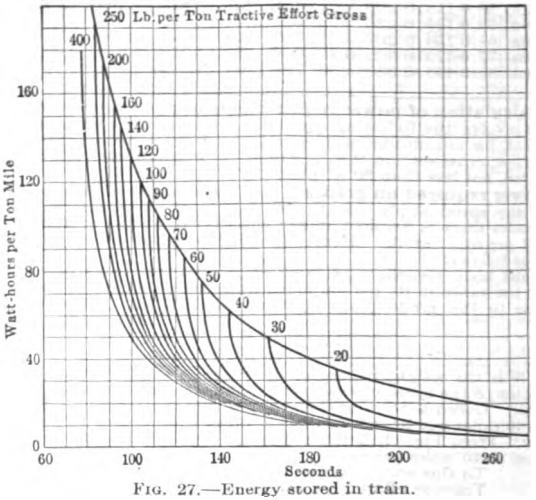


FIG. 27.—Energy stored in train.

The most convenient form of expressing energy values is in watt-hours per ton-mile. Fig. 27 has been constructed from the speed-time data in Fig. 20, giving the energy consumption for any rate of acceleration and elapsed time for a distance of 5,280 ft. or 1 mile run. This set of curves is plotted with train resistance = 0, and hence represents the value of the energy of acceleration only.

90. Energy dissipated in braking. In bringing a train to rest by means of brakes, the energy stored in the train during acceleration and represented by $mv^2/2$ is all wasted in heating the wheels and brake shoes, and the values in Fig. 27 therefore represent the energy thus dissipated as heat. The curves have no value as applying directly to service conditions as all moving trains have more or less running resistance, but they are useful as indicating the energy required to accelerate the mass, all of which reappears as heat in the brake shoes and car wheels, unless some method of regenerative braking be used (Par. **114, 115** and **116**).

91. Curves of energy consumption. Unless the train reaches a speed of more than 40 miles per hr. it is a sufficiently close approximation for preliminary calculations to assume a constant rate of train resistance of from 10 to 15 lb. per ton, the latter figure being the more conservative value. Hence, Figs. 28 and 29 are plotted with a constant value of train resistance at all speeds of 10 and 15 lb. per ton respectively. These curves used in

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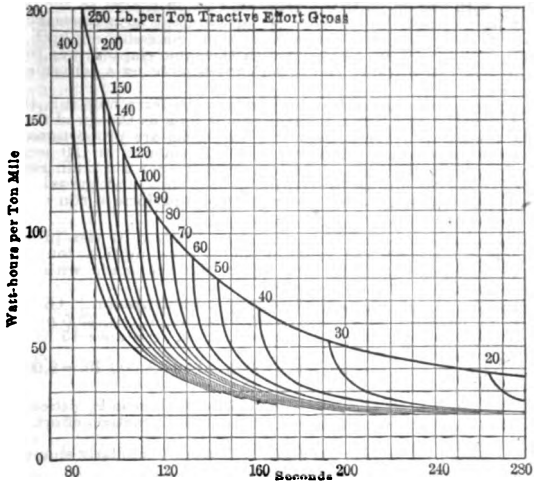


FIG. 28.—Energy consumption (train resistance equals 10 lb. per ton).

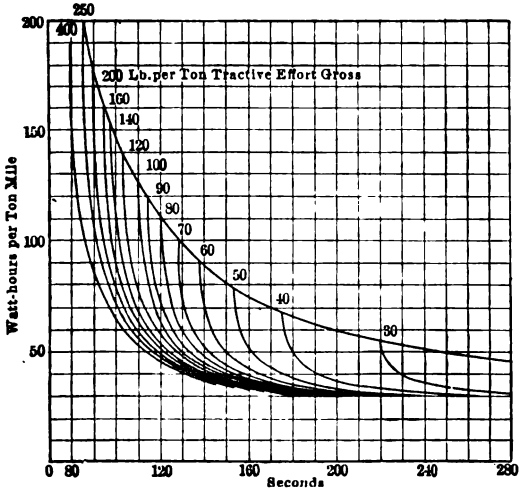


FIG. 29.—Energy consumption (train resistance equals 15 lb. per ton).

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conjunction with the speed-time curves of Fig. 20 permit of the complete solution of any acceleration problem so far as relates to performance of the train and its net energy consumption. For convenience, both speed-time and energy curves are made up with the same elapsed time for a mile run as abscissa, this distance run being chosen as being a convenient basis for comparison.

Having determined the watt-hours per ton-mile for a mile run, the same value holds true for any other distance run as long as the speed-time curve is entirely similar in every respect and the areas are proportional to the respective distances run. Thus, a mile performance in 120 sec. with a tractive effort of 90 lb. per ton (including 15 lb. per ton train resistance) will require an output rate of 73 watt-hr. per ton-mile, and the same energy, 73 watt-hr. per ton-mile, would be required to perform a run of half the distance in $1/\sqrt{2}$ times 120 sec., or 84.8 sec.

Thus while the speed-time curves must be changed in area proportional to the distance travelled, the value of energy consumption found for one distance holds equally true for any other distance made with a similar speed-time curve.

92. Example of calculation of energy consumption. Given a run of 1,760 ft. to be made in 75 sec., train weight 100 tons, 33.5 per cent. on drivers, coefficient of adhesion 12 per cent., train resistance 15 lb. per ton. Find energy consumption.

Available tractive effort = $200{,}000 \times 0.335 \times 0.12 = 8{,}000$ lb. = $8{,}000/100 = 80$ lb. per ton.

To reduce to mile basis $\sqrt{5{,}280/1{,}760} \times 75 = 130$ seconds. (See Par. 48.)

From Fig. 29, 1 mile in 130 sec. with 80 lb. tractive effort gives 61 watt-hr. per ton-mile.

The same value, 60, is true for 1,760 ft. made by similarly shaped speed-time curve in 75 sec.

93. Motor-curve acceleration. Instead of being able to accelerate a train at a uniform rate until maximum speed is reached, all types of electric motors operate best with a certain amount of motor-curve acceleration at a rate constantly falling off from the initial or straight-line acceleration which is only carried part way to full speed. Also, the electric motor has internal losses, electrical and mechanical, which together with certain losses inherent to its system of control make it necessary to add a greater or less percentage to the net energy-consumption curves given in order to obtain the *input* to the train. The different types of motors have their distinctive internal losses and type of control, and the performance relation of the several motor equipments to the net energy-consumption curves is best expressed by the efficiency of acceleration of the several systems.

94. The efficiency of acceleration is the percentage of the net energy consumption of motor output, to the gross input of the train. The values given in Figs. 28 and 29 hold true as the net output of any type of motor and control system, hence, given the efficiency of acceleration of any system, the net energy values form the basis of calculating train inputs for any operating conditions. See Par. **97, 107** and **112.**

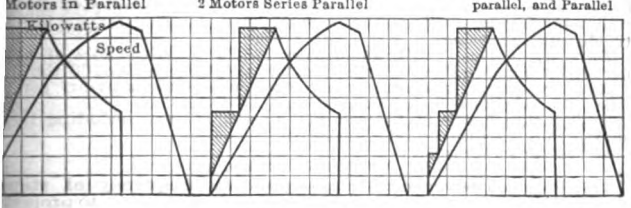
The losses in the motor equipment during acceleration are divided into internal motor losses including loss in gears, and losses incident to method of control.

95. Internal motor losses consist of copper I^2R in armature and field, hysteresis and eddy-current losses in the iron circuit, brush-friction and I^2R loss, bearing friction and gear losses. All these losses are included in the curves furnished by the manufacturers for normal 500 volts constant potential at the brushes, but no such values are readily available for fractional-voltage operation during the accelerating period.

96. Starting resistance losses. It is customary to assume full-load current of a railway motor during the straight-line acceleration period, and at standstill the IR drop in the motor copper will approximate 50 volts. It is necessary, therefore, to provide sufficient starting resistance in series with the motor to take up the remaining 450 volts or the difference between the line potential and the motor copper drop. This starting resistance is cut out in successive steps as the motor armature gains speed and establishes its own counter-electromotive force, until a period is reached, when the starting resistance is entirely short-circuited and the full line e.m.f. is just sufficient to maintain full-load current through the motor. This period completes the

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ght-line acceleration, as after this point the series-wound motor will still erate the train, but at a constantly decreased rate, until full constant d is attained. It is evident then, that a large amount of power is con- ed in the starting resistance and to reduce this excessive loss at starting, nethod was introduced of connecting two motors in series during half the od of straight-line acceleration, thus reducing the amount of starting tance required (Par. 49).



. 30.—Direct-current control of series-wound motors (shading shows loss in starting rheostat)

current-input curve is plotted for the three methods of control of ect-current railway motors in Fig. 30 the shaded portion indicating the rgy lost in heating the starting resistances, and showing the economy ned by starting with motors in series. This economy is expressed merically in Par. 97.

Efficiency of acceleration direct-current series-wound motors (Par. 94)

Per cent. of straight-line acceleration. (See Par. 98)	Motors, parallel. (Per cent.)	Two series parallel. (Per cent.)	Four series, two series-parallel. (Per cent.)
100	43	56.0	60.5
90	46	59.0	62.5
80	49	62.0	65.0
70	52	64.0	67.0
60	56	67.0	69.0
50	58	69.0	71.0
40	62	71.0	72.5
30	65	72.5	73.5
20	68	73.5	74.0
10	72	74.5	74.5
0	75	75.0	75.0

98. The per cent. of straight-line acceleration is the ratio of the ne constant current is supplied, to the total time current is supplied to e motors, and it thus becomes a measure of the shape of the speed-time rve. In typical rapid transit service, the constant accelerating period from 25 per cent. to 35 per cent. of the total time during which power is pplied before coasting and braking begins.

Hence, 100 per cent. of straight-line acceleration denotes the fact that e cutting out of starting resistance has just been accomplished, while per cent. of straight-line acceleration means that the train is running free, full speed, at the free-running efficiency of the motors.

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99. Example of calculation of energy consumption during acceleration with the two-motor series-parallel combination. In this system the efficiency of acceleration ranges from 56 per cent. to 75 per cent. A typical speed-time curve will require approximately 30 per cent. of straight-line acceleration, hence, the efficiency of acceleration which meets general operating conditions, will be approximately 73 per cent. for geared motors of 75 h.p. or over and 68 to 73 per cent. for smaller motors. The value of 73 per cent. efficiency may be used directly in connection with the energy values given in Fig. 30, that is, the energy-curve values divided by 0.73 will give the gross train-input watt-hours per ton-mile at the train, allowing for no losses in the distribution system.

Example: Given a mile run made in 135 sec., tractive effort of 119 lb. per ton including 10 lb. train resistance, find average input for 100 ton train.

Answer: From Fig. 30, energy consumption net = 38 watt-hr. per ton-mile. Input = 38/0.73 = 52 watt-hr. per ton-mile.

Train makes 1 mile in 135 sec. = 1 mile in 147 sec., including 12 sec. stop = 24.5 miles per hr. schedule speed.

Hence, the power input is

$$P = 52 \times 100 \times 24.5 = 127 \text{ kw. per hr.}$$

100. Relation between schedule speed and frequency of stops. As shown in Par. 102. In other words, an effort has been made to proportion properly the maximum free-running speed of the equipment to the schedule speed obtaining for a given number of stops per mile. Thus an equipment operating with one stop per mile can make 24 miles per hr. schedule with stops of 12 sec. and should properly be geared for 40 miles per hr. If the equipment were geared for higher maximum speed than 40 miles per hr., the resulting schedule speed would not be much in excess of the 24 miles per hr. given while the power consumption would have been considerably greater. On the other hand, an equipment geared for somewhat lower maximum speed than 40 miles per hr. could still make 24 miles per hr. schedule with a 12-sec. stop occurring at every mile, but requiring a higher rate of acceleration than the 1.1 m.p.h. per hr. per sec. assumed. As a high rate of acceleration is undesirable with high-speed equipments, the rates given in the table should not be greatly exceeded unless there are strong local reasons making such high rates necessary.

101. Interruptions to service treated as "equivalent stops." The table of schedule speed includes little or no leeway to make up for lost time and where such interruptions of service are liable to occur they should be treated as additional stops per mile, and the proper schedule speed, maximum free-running speed, etc., should be taken for the *equivalent* number of stops per mile, including actual stops, slow-downs for curves, crossings, etc., and a margin for unexpected delays. Thus, with one actual stop of 15 sec. duration occurring every 2 miles, there may be slow-downs for curves, etc., making the equivalent number of stops approximate one per mile, in which case a 24-mile per hr. schedule with 40 miles per hr. maximum speed of equipment would be a safer estimate of speed possible than the 32 and 40 miles per hr. respectively given for one stop in 2 miles. In other words, keep the maximum speed of the equipment at the lowest value that will admit of maintaining the schedule desired with the frequency of stops given. Not only is there a saving in energy consumption resulting from the use of lowest possible maximum speed, but, as will be shown later, there is also a large saving in the capacity of motor required to perform the service.

102. Train input in kw., frequent-stop service, tangent level track.

Stops per mile	¼	½	¾	1	2	3	4	5	6	7
Schedule speed, miles per hr.	50.0	40.0	32.0	24.0	18.5	15.5	13.7	12.5	11.7	11.(
Maximum speed, miles per hr.	65.0	55.0	45.0	40.0	30.0	25.0	23.0	21.0	20.0	19.(
Stops, seconds.....	30.0	20.0	15.0	12.0	10.0	9.0	8.0	7.0	6.0	5.(
Eff. of accel., per cent.	75.0	75.0	75.0	74.0	72.0	70.0	69.0	68.0	67.0	65.(
Accel., miles per hr. per sec.	0.8	0.9	1.0	1.1	1.2	1.3	1.4	1.5	1.6	1

The above data are common to all trains.

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ops per mile	⅛	¼	½	1	2	3	4	5	6	7
ton car.....			51	36	29	26	24	23	22	22
ton car.....		96	69	51	40	36	33	32	31	31
ton car.....	176	119	85	63	51	45	43	41	40	40
ton car.....	195	130	94	73	61	55	52	50	49	49
ton car.....	200	140	106	82	70	64	62	60	59	58
20 ton cars..			78	60	50	45	43	41	40	40
30 ton cars..		137	104	80	69	64	62	60	59	58
40 ton cars..	228	160	124	103	89	82	79	77	76	75
50 ton cars..	255	183	147	125	111	103	99	97	95	94
60 ton cars..	282	202	165	144	127	117	115	113	111	110
20 ton cars..			102	76	67	63	61	60	59	58
30 ton cars..		173	135	112	97	90	88	86	84	83
40 ton cars..	280	200	164	140	127	117	115	113	111	110
50 ton cars..	300	236	198	172	155	145	142	139	137	136
60 ton cars..	342	263	219	191	175	167	163	160	158	157
20 ton cars..			144	124	110	102	98	97	95	94
30 ton cars..		238	196	171	154	145	142	139	137	136
40 ton cars..	370	292	246	216	197	188	183	180	178	176
50 ton cars..	438	350	302	270	250	236	228	225	222	220
60 ton cars..	495	400	352	314	290	280	275	271	266	263

These train resistances corresponding to the different train weights agree th Figs. 9 to 14.

103. Suburban cars in city service. While the values given in the table ver the entire field of rapid transit service from seven stops per mile to one op in 8 miles, it frequently happens that the relation between maximum d schedule speed given cannot be approximated in actual service operation ring to peculiar local requirements. Thus a suburban car, operating at miles per hr. maximum, may be called upon to operate in city service at rminals or en route where the frequency of stops approximate six per mile, ondition properly calling for a maximum speed of 20 miles per hr. The wer consumption given for six stops per mile would be greatly increased in e case of a high-speed suburban car operating on such service, even though ries running were adopted exclusively in the city service. Series running ould then correspond to the efficiency of acceleration given in Par. 97, for l motors in parallel, and would thus be 10 per cent. or more lower than for ries-parallel operation; hence the figures for kilowatts input at train given the table represent minimum values resulting from a proper proportion tween the maximum free-running speed of the equipment, the schedule eed and the frequency of stops.

104. For rates of acceleration other than those given in the table ar. 102), where the frequency of stops is greater than one per mile, any ecial case should be worked out from the general watt-hour-per-ton-mile rves (Figs. 28 and 29).

105. Frequent-stop service for electric locomotives is not treated re as it is assumed that the legitimate field of the locomotive is in express rvice having very infrequent stops, in which case the energy of acceleration rms but a small percentage of the total input of the train.

106. The single-phase railway motor, being a series-wound type, can e operated by means of non-inductive external starting resistance as in e case of the direct-current series-wound motor. Owing, however, to the cility with which alternating voltage may be varied by static transformers, better method of control is offered by means of shifting the motor terminals om tap to tap, brought out from the step-down transformer or compensator nstituting part of the car equipment. The potential control thus made ssible introduces no losses commensurate with the starting resistance losses direct-current motor control, and is the most efficient form of control yet olved for railway work.

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The accelerating efficiency of an induction-motor railway equipment indicated for parallel operation only, concatenation not being considered. a straight-line acceleration will constitute fully 50 per cent. of the total riod during which power is supplied in a typical rapid-transit run, an duction-motor equipment will have an efficiency of acceleration not to ceed 55 per cent. This represents the power efficiency and does not include e power-factor which will approximate 80 per cent. during acceleration ith non-inductive resistance inserted in the secondary circuit, thus making e *apparent* efficiency of acceleration approximately 44 per cent.

Hence, for acceleration problems involving a consideration of railway duction motors of the polyphase type, divide energy values given in gs. 30 and 31 by 0.44 to obtain the volt-amp. input at the train and *not cluding* any trolley or distribution losses. The proper field of the induction otor is the haulage of trains at constant speed behind locomotives and the e of this motor will be further discussed under Locomotives.

113. Regenerative (dynamic) braking. In service calling for frequent arting and stopping of trains, it is evident that the $mv^2/2$ constituting the nergy loss in heating brake-shoes and wheels, forms a considerable per- ntage of the total energy input to the train. As the electric motor is versible, that is, can absorb power and give out mechanical energy, or can ve out electric power when mechanically driven as a generator, it seems ssible to expect that some means of control can be designed which will able a train to be braked electrically with reduced wear and expense of rake-shoe maintenance, besides returning to the line a considerable per- ntage of the energy delivered to the train during acceleration. Also on ads having excessive continuous grades, it is desirable to return energy to ne line partly for the economy thus effected, but largely in order to reduce ne danger that goes with braking long heavy trains by means of brake-shoes.

114. Motor capacity for regenerative braking. The standard direct- rrent motor, being of the series-wound type, cannot be used directly as a irect-current generator, and some modification of shunt winding or excita- on of the series field at low potential must be used in order to enable the otor to act as generator when braking the train. Of the total energy elivered to the train during a typical city run, nearly one-third of the amount wasted due to the inefficiency of the motor, gears, and method of control. f the remaining two-thirds, fully 25 per cent. is to overcome train sistance, leaving 50 per cent. of the original train input as available for generative purposes. Owing to the complications required to make a series irect-current motor equipment available for generation, it would not be ossible to effect the same efficiency of deceleration as the 70 to 75 per cent. ossible during acceleration. Furthermore, the capacity of a railway motor o do work is limited by its heating, and this heating is dependent upon the uperficial area and weight of the motor, hence, if the motor is chosen with ue regard for its safe temperature rise when used for accelerating the car. s thermal capacity must be increased in due proportion to the amount of xtra motor loss entailed in electrically braking the car. This extra weight f equipment will in turn entail an additional expenditure of energy during he accelerating period, so that the effect of braking the train electrically rith the same motive power used for acceleration, will be to increase the duty f such motors considerably, and, hence, their weight and first cost.

115. Economy of regenerative braking. Assuming that an efficiency f 60 per cent. could be obtained during retardation by electric braking, it ould mean the possible saving of 30 per cent. in the energy consumption f the car, provided the car weight were not increased due to the larger otor capacity demanded. It is not possible, however, to effect any such conomy as the figure indicated, and from 15 to 20 per cent. saving of gross nput would more nearly represent the possibilities of regenerative control, n a class of service calling for very frequent stops. It is evident that where tops are infrequent as in high-speed interurban service, the effect of regenera- ion would become negligible so far as economy of operation is concerned.

116. The first cost of regenerative control, and the increased cost f maintenance offset the advantages derived from a possible smaller energy onsumption of the car. It is not too much to expect that the car equipment will be increased fully 50 per cent. in weight and first cost if regenerative con- rol be adopted, and the possible 15 to 20 per cent. energy must be balanced

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against the interest on the additional first cost and cost of maintaining the equipment.

As any system of regenerative control depends upon the counter e.m.f. of the revolving armature, it is evident that when approaching zero speed there will be no torque developed by the motor, and hence, regenerative braking must be used in connection with air brakes, with resultant decrease saving in economy. For street-car service, including interurban service it can be said that there is small attraction in regenerative control, not because such control is not possible, but because the added complication and expense brings no adequate return in the cost of the energy saved.

117. Regenerative control used in connection with locomotives for heavy passenger or freight service on mountain-grade sections offers many advantages far outweighing in importance the possibility of small amount of energy saved. One of the disadvantages attending the operation of long heavy trains on mountain grades, is the danger incurred in braking the trains on the down grades. More accidents occur when trains are running down grade than when operating up grade, due to the fact that overheated brake shoes and car wheels may cause a derailment, and also due to breaking apart of long trains when the brakes are released momentarily for the purpose of recharging the train pipe. On such classes of service, a regenerative system of control offers safer means of holding trains on down grades than exists with present air-brake control, and its use in this direction make it worthy of very careful consideration for this class of service. Also see "Electric Locomotives," Par. **260**, et seq.

118. Westinghouse direct-current regeneration system. The system of regeneration used with direct-current railway motors by the Westinghouse Electric & Manufacturing Company is fundamentally shown as in Fig. 31. This figure shows the armature of the main motor, *A*, the main motor field, *F*, the balancing or stabilizing resistor, *R*, and the exciter, *E*. Inherently, a series direct-current generator has no stability of voltage and some external means is necessary to control it when regenerating. In the figure, the exciter, *E*, furnishes current which flows in the path indicated by the dotted arrows. This current excites the main motor field and causes the armature, *A*, to generate a voltage opposed to the line voltage. The voltage of *E* can be regulated either by regulating its field strength or by inserting or removing resistance in series with its armature. When the voltage of *A* overcomes the line, a current starts to flow from the ground through *R* and *A* to the line. Thus *R* carries both the main regenerated current and the exciting current.

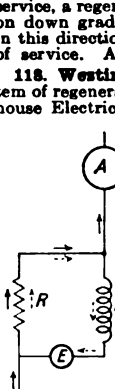


FIG. 31.—Direct-current regenerative braking.

The stabilizing effect comes from the resistance *R*, since any variation in the regenerated current will vary the drop across the resistance and thus, assuming the voltage of the exciter, *E*, to be fairly constant, will have an immediate effect on the field of the main motor to counteract such a variation. For instance, if a train is regenerating down grade with the exciter voltage set so as to give the proper excitation to the main field to furnish the necessary braking effort, and the line voltage should suddenly drop, the regenerated current would immediately tend to increase. However, the increased current which tends to flow, increases the voltage drop across the resistance *R*, and directly reduces the exciting current, thus maintaining a balanced condition as before.

It is important in a direct-current regenerating system, to have this regulating influence as nearly direct as possible, since, changes in line voltage may, at times, be so great and so sudden that unless the regulation is simultaneous with the variation, a condition of unbalance between the armature and field of the motor may be sufficiently great to cause flashing at the commutator.

The excitation for the main motors is supplied by a separate generator driven either by a motor or from an idle locomotive axle through gearing. The regulation of the braking is then obtained by varying the exciter field strength or by varying the amount of resistance in the stabiliser circuit.

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19. Alternating-current regeneration. Regeneration with poly-ase motors is obtained very simply by driving the rotors above synchronous ed. No change in connections or separate means of excitation are re-red. This method of regeneration has been in successful operation for umber of years.

everal schemes of regeneration with single-phase commutating motors e been devised, but none have been put in operation in this country, ough a form of regeneration or dynamic braking has been placed in ration in Switzerland by the Oerliken Co.

RAILWAY MOTOR CAPACITY

20. Limitations of design. The capacity of railway motors to do work not be measured by the same standards governing the rating of motors the stationary type. Conditions of operation demand that the motors ll conform to the requirements of a 4 ft. 8½ in. gage track, and fre-ntly a wheel base of not over 78 in., and preferably less. The re-cted space thus available makes it imperative that the weight and out-e dimensions of railway motors shall be scaled to the lowest possible limit sistent with the average and momentary output demanded by service uirements. It is customary, therefore, in railway-motor design, to force density of the magnetic circuit far in excess of what is considered good ctice in the design of stationary motors. The effect of this high satura-n of the iron circuit is to entail an iron hysteretic and eddy-current loss uch a high value as to preclude the possibility, in many cases, of running motor continuously at full voltage without overheating it due to the loss alone. It is evident, therefore, that recourse must be had to methods comparative rating of railway motors other than the usual continuous ning at full voltage, obtaining in the case of stationary motors. On omotives these space restrictions can be largely overcome by use of the e-rod drive with the motor mounted above the wheels.

21. The nominal rating of a railway motor is given in the A. I. E. E. ndards, Sec. 24, Par. **5202.**

22. The continuous-rating input of a railway motor is given in the I. E. E. Standards, Sec. 24, Par. **5203.**

23. The maximum load on railway motors does not usually exceed 150 cent. of the nominal rating.

24. Two factors determine the capacity of railway motors, namely nmutation and heating. During the accelerating period the current input nanded by a railway motor is always considerably in excess of the current erward required to run the car at full speed on level tangent track. The lue of this current will depend upon the several conditions entering into problem, weight of train, schedule speed, and frequency of stops, these tors determining the rate of acceleration and maximum speed required as viously outlined. A motor must be selected which can commutate the normal current required during the accelerating period without excessive rking at the brushes.

25. Division of load between motors. For close calculations it is essary to plot the actual speed-time curves obtaining with any individual tor. In dividing the total current input to the train by the number of tors, in order to obtain the current per motor, it can be assumed that h motor will take its equal share of current at all speeds, provided the mo-s are of the same type and capacity, and have the same gear ratio.

26. Effect of acceleration rate and maximum speed on capacity. is evident from working out a few examples, that high rates of acceleration be used only when low maximum speeds are possible, and that an normally large motor capacity will be essential if high rates of acceleration demanded in connection with high maximum speeds. Thus, although tor equipments of the direct-current series-wound type can always nish enough current to slip the driving wheels, such high current inputs ll be demanded as will considerably exceed the safe rated commutating pacity of motors operating cars at 50 miles per hr. or more, common to erurban high-speed service. Various devices have been brought out for purpose of limiting starting currents to safe predetermined values, and current-limiting device now forms a component part of certain types of trol equipment.

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127. The heating of railway motors in operation is caused by internal copper, iron and brush losses. These losses vary not only in intensity but also in distribution with different types of motors and classes of service. At zero speed, the losses are all in the copper of field and armature, being divided according to their relative resistance. As the armature speed increases there is an iron loss distributed between the iron of armature and pole face and tips, depending upon the design of the motor. This iron loss starts from zero at standstill and increases to a maximum at the moment of cutting out starting resistances, after which it decreases somewhat; this again is a matter of motor design. As the various losses are the cause of temperature rise in the motors, it is necessary to trace their influence upon the individual part of a motor under study.

128. Internal motor losses. As the heating of a motor is the result of the average losses within it, the average losses and their distribution up to any moment of shutting off power must be determined.

Internal motor losses during fractional-speed running are indicated in Fig. 32 where abscissas give elapsed time and ordinates represent power loss. In other words, the losses depicted are not instantaneous losses at any given speed, but integrated losses from the time of starting from rest, to gaining that speed.

Equally important with the determination of the various internal losses is their distribution. Thus in a closed motor the armature loss must be conducted through the field structure before it can reach the outside surface of the motor and be dissipated into the surrounding air. Added to the heat imparted to the field structure by its own I^2R losses and pole face losses there is, therefore, considerable heat delivered to it by virtue of its service as a conducting medium for the armature heat. On the other hand, the field structure would conduct the armature heat at a more rapid rate were it not for its own internal loss. It becomes important to establish a relation for this interchange of heat between field structure and armature, the relation best expressed by the ratio of armature loss to field loss, as indicated in Fig.

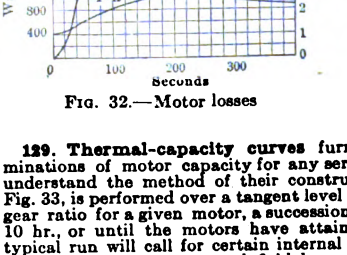


FIG. 32.—Motor losses

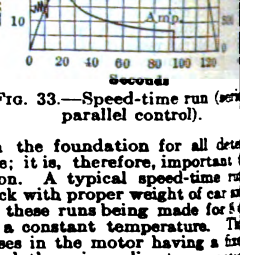


FIG. 33.—Speed-time run (series parallel control).

129. Thermal-capacity curves furnish the foundation for all determinations of motor capacity for any service; it is, therefore, important to understand the method of their construction. A typical speed-time run, Fig. 33, is performed over a tangent level track with proper weight of car and gear ratio for a given motor, a succession of these runs being made for 8 to 10 hr., or until the motors have attained a constant temperature. The typical run will call for certain internal losses in the motor having a fixed ratio between armature and field losses, and there is a direct connection between these losses averaged over the 8 or 10 hr. run and the temperature rise of the several parts of the motor. Fig. 34 is thus constructed from results of a series of such temperature runs, each separate 10-hr. run giving rise to a certain ratio of armature to field losses, and therefore establishing one point upon the field and armature thermal-capacity curve.

130. Application of continuous rating. The continuous rating of railway motors (see Par. **122**) differs from that of constant-speed motors in that it is based not on the normal voltage of the motor but on voltages which combined with the rated continuous current, will give the average core loss corresponding to the particular service. For convenience the continuous

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rating is given in amperes at half, three-fourths and full voltages. To determine the sufficiency of the motor for a given service, a typical speed-time run should be plotted and from that the square-root-of-the-mean-square (r.m.s.) current should be obtained. This should correspond to the rated continuous current. With the modern self-ventilated motors, this practically controls the temperature, since the increased speed that goes with higher core losses, also causes a better circulation of air through the motor and carries off more heat. It is found that ventilated railway motors carry practically the same current at all voltages. Enclosed motors carry 5 to 10 per cent. more current at the lower speeds corresponding to low voltages and frequent stopping service than at higher speeds and voltages corresponding to interurban service.

131. Application of thermal-capacity curves. Any given service operation, although made up of short and long runs, can be resolved into a single typical speed-time curve which will call for the same internal losses and the same distribution of motor losses as would obtain under service conditions. By utilising data as given in the thermal capacity curve, Fig. 34, for a given motor, it is possible to predict, with reasonable accuracy, the temperature rise of a motor for any operating conditions coming within the limits of the motor capacity. As such calculations demand a vast number of experimental runs, the expense of which can only be borne by railway-motor manufacturers, some better form of expressing the relation of railway motor capacity and service performance is necessary for approximation work. Owing to the fact that railway motors of the direct-current series-wound type have become standardized along certain lines, it is possible to establish a working relation between the commercial 1-hr. rating of a motor and its ability to do work under service conditions.

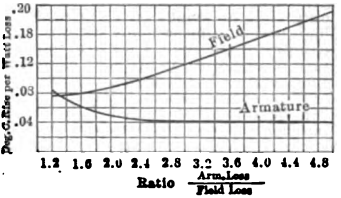


FIG. 34.—Thermal characteristics.

132. Service capacity curves. Applying results similar to Fig. 34, to a series of speed-time curves for different distances run, a curve similar to Fig. 35 is obtained for an equipment having a fixed gear ratio, in this case proportioned for a maximum speed of 45 miles per hr. on tangent level track. This curve, called a service capacity curve, gives directly the temperature rise for a given equipment, in this case a 125-h.p. motor, for any schedule speed that can be performed with a varying number of stops per mile, the equipment being geared for 45 miles per hr. maximum speed when running free.

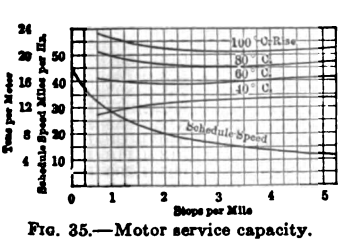


FIG. 35.—Motor service capacity.

It will be noted that the tons train weight per motor for a given temperature rise do not vary greatly over the whole range from five stops per mile down to less than one stop per mile. In other words, a railway motor equipment of fixed gear ratio when mounted on a car of fixed weight, will attain approximately the same temperature rise above the surrounding air, irrespective of the number of stops per mile demanded by service conditions. Thus from Fig. 35, 16 tons per motor gives temperature rise of 60 deg. cent. for the motor under consideration, and this temperature rise holds good whether the car is making a schedule speed of 11.5 per hr. with five stops per mile, or 29 miles per hr. with one stop per mile.

This fact furnishes a means of simplifying the expression giving the relation between the 1-hr. commercial capacity test and service capacity of the railway motor. It is sufficient for purposes of approximation to rate a given motor at the tons train weight per motor which can be hauled for a given maximum speed or gear ratio, taking say 60 deg. cent. rise as a basis.

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133. Short method of determining horse-power rating of trolley car equipments. Because of the many conditions which have to be take into account in the selection of motors for various classes of trolley c service and the varying characteristics of railway motors, some such proce as outlined above is usually adopted when close recommendations are r quired. The process is too elaborate for approximate estimates and becau of this there are several approximate short-cut methods which are some tim used. There is a feeling, however, that there are many cases where t service can be made more or less to fit the equipment and the problem bo down to a selection of a rational equipment for various weights of trai geared for various maximum speeds. For short-stop city service the eco omy of light-weight cars geared for low maximum speeds and capable high acceleration is being appreciated more and more. In considering t equipment for such a service the motors will be required to give a hi rate of acceleration without exceeding the 1-hr. rating, whereas for hig speed service the accelerations are not so frequent and high rates of acc eration are not so essential, consequently the 1-hr. rating of the moto can be somewhat exceeded during acceleration. Thus cars geared for maximum speed of 25 m.p.h. should be equipped with motors which c accelerate the car at approximately 1.5 m.p.h. per second without exceedi the one-hour rating of the motors, whereas cars geared for 50 m.p. probably would not be used in a service where they would have to acc erate at more than 1 m.p.h. per second in which case a motor equipme which would produce this acceleration at 30 or 40 per cent. overlo would ordinarily have sufficient capacity to handle a service which wou require such a high maximum speed. The following table (Par. **134**) h been prepared along these lines to show relatively the horse-power capaci for low- and high-speed service and is useful as a means of selecting from list of standard motors the equipment which will come nearest meeting t requirements of any particular service. A temperature rise of 65 deg. ce has been taken in order to ensure a reasonably long life to the motor insul tion, a much higher temperature rise causing a too rapid deterioration. I this connection may be mentioned the possibility of running motors at mu higher temperature when they are provided with mica and asbestos insul tion with no fabric.

134. Horse-power motor capacity required; standard direct-curre railway motors, ventilated type

Max. speed, m.p.h.	Weight of train including passengers, tons												
	20	30	40	50	60	80	100	120	150	180	200	250	30
25	103	142	181	215	248	312	375	435	526	610	667	824	97
30	116	160	202	240	278	346	419	483	580	673	734	900	1.07
35	131	179	226	268	309	383	461	531	638	738	807	993	1.17
40	...	200	250	298	341	419	505	579	695	802	877	1,080	1.27
45	...	...	275	326	372	450	549	632	754	872	955	1,165	1.37
50	...	...	...	360	408	502	600	685	818	940	1,030	1,257	1.47
55	...	...	...	392	442	548	651	744	885	1,013	1,116	1,358	1.58
60	...	...	...	...	483	596	708	802	960	1,097	1,200	1,458	1.68
65	...	...	...	...	528	640	759	863	1,025	1,169	1,280	1,559	1.78

The horse-power capacity required conforms to the commercial rating railway motors, that is, the 1-hr. horse-power rating defined by the A. I. E. Standardisation Rules (Sec. 24, Par. **202**).

135. Division of train horse-power capacity. The horse-power capa ity given for any train weight may be split up into the required number units. Thus, a train composed of five 40-ton cars running at 45 m per hr. requires 955 h.p. motor capacity. This may be divided into units of 160 h.p. each, that is, three motor cars equipped with double h.p. motors hauling two trailers, or each car of the train may be a motor and be equipped with a pair of 100-h.p. motors. Approximately the sa temperature rise will obtain in either case.

Certain motors of modern construction provide for longitudinal ventilati either with blower on armature or with external blower. In either case, t

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armature and field losses are carried off independently of each other by the introduction of external air, hence the ratio of losses in such motors becomes of secondary importance.

136. Division of capacity for single cars and trains. For single-car operation a four-motor equipment is preferred for double-truck cars, this being especially true where snow or heavy grades are characteristic of the service. For train operation, two-motor equipments are used, as the disabling of a single unit will not incapacitate the train.

137. Power requirements with single-phase equipment. Owing to the short period during which single-phase motors have been operated, their design has not yet become standardized, nor is there sufficient operating data upon which to base anything more than general conclusions of the horsepower required for a given service. The single-phase motor is essentially a high-speed motor, having a high copper loss and low core loss, hence, is more particularly adapted to constant-speed running, and suffers in comparison with the direct-current series wound motor when used for acceleration work. There is no lack of starting torque with the alternating-current motor, but a large tractive effort is obtained only at the expense of a large copper loss, so that alternating-current motors are unsuitable for rapid transit service demanding repeated high rate of acceleration, not because such motors cannot furnish the tractive effort required, but because the copper loss incident to such high tractive efforts will heat the motors unduly if used exclusively for acceleration service. Thus the alternating-current motor becomes much heavier than the direct-current motor on the basis of service performed with frequent stops.

138. Single-phase equipment for a service embracing infrequent stops. In interurban or express service with infrequent stops, the smaller core loss of the alternating-current motor brings it more nearly on a par with the direct-current series wound motor as regards output per pound weight of motor. It is possible therefore to use the figures of Par. **134** as applying to alternating-current motor capacity, where stops are not greater than one in 2 miles. However, the table should not be used in connection with higher frequency of stops given, as then the resulting motor capacity indicated in the table must be largely increased when applied to alternating-current motors.

Owing to the fact that the chief advantage of the single-phase motor lies in its ability to utilize the benefits of trolley potentials of 11,000 to 15,000 volts as compared with the 600 to 3,000 volts used with direct-current motors, questions of safety limit the field of operation of alternating-current motors to lines operating over private rights of way except where alternating-current-direct-current equipments are used or a lower alternating-current voltage is used on the trolley as is sometimes done.

139. Three-phase equipment. Owing to the few applications of three-phase induction motors to motor cars, no statements can be made regarding the capacity of such motors for service performed. The induction type of alternating-current motor is not at all adapted for acceleration work, owing to the poor efficiency of the car equipment during fractional speed running. The field of the three-phase induction motor lies in the direction of a service calling for constant effort at constant speed, and the problems wherein this type of motive power can be considered are so special and infrequent as to place it entirely beyond consideration for general motor car application.

140. Locomotive motors. Locomotive operation demands a special treatment of the motor capacity subject, in most cases requiring such special knowledge of the motor construction as to prevent any general conclusions being drawn with the limited data at hand. The locomotive motor is designed more along the lines of a stationary motor, that is, owing to the necessity for operating a locomotive close to the tractive limit, its motive power is running continuously at nearly its full-load. With a locomotive working at 75 per cent. or more of the slipping point of the drivers, there is a possibility of but small overload and hence the motors may be designed with lower density, in fact like a stationary motor. With the absence of extreme overloads, the question of commutation becomes secondary and the selection of a motor becomes a matter of its ability to radiate the heat generated for the service specified. The whole question of motor capacity for locomotives is so intimately connected with mechanical problems of loco-

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motive design, that it must be placed in the list of special problems requiring the careful cooperation of the manufacturers. Locomotives for switching service use the motor intermittently, and the above remarks do not apply.

141. Standard General Electric railway motors, commutating-pole type

600 Volts

Type	H.p.	No. of motors	Type of control	Weight (lb.)	
				Motor	Total equipment
258-C	25	2	K-63	885	2,520
		4	K-35		4,830
		4	PC		4,940
258-D	25	2	K-63	1,000	2,750
		4	K-35		5,290
		4	PC		5,400
264-A	25	2	K-63	1,005	2,760
		4	K-35		5,310
		4	PC		5,420
264–B	25	2	K-63	1,130	3,010
		4	K-35		5,810
		4	PC		5,920
200	40	2	K-63	2,115	5,080
		4	K-35		9,950
		4	PC		9,940
247-A	40	2	K-63	1,740	4,330
		4	K-35		8,450
		4	PC		8,440
247-D	40	2	K-63	1,870	4,590
		4	K-35		8,970
		4	PC		8,960
203	50	2	K-36	2,630	6,470
		2	PC		6,510
		4	K-35		12,040
		4	PC		12,020
201	65	2	K-36	2,845	6,990
		2	PC		7,140
		4	K-35		13,060
		4	PC		13,040
263-A	65	2	K-36	3,050	7,400
		2	PC		7,550
		4	K-35		13,780
		4	PC		13,970
240	110	2	PC	3,840	9,560
		4	K-64		18,160
		4	PC		17,870
259-A	120	2	PC	4,000	10,200
		4	PC		18,600
254-A	140	2	PC	4,515	11,410
		4	PC		20,960
248	160	2	PC	5,720	13,780
207	165	2	PC	5,200	12,740
260	195	2	PC	5,745	13,970
212	225	2	PC	6,050	14,690
			600/1,200 Volts		
263-A	55	4	PC	3,050	15,800
240	90	4	PC	3,840	19,000
207	110	4	PC	5,200	24,530
207	140	4	PC	5,200	24,810
254	145	4	PC	4,480	22,070

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142. Forced ventilation is being resorted to especially in the case of the arger motors for locomotives, as owing to the limits imposed by standard :age and allowable wheel base it often becomes extremely difficult to concen-rate the required motor power without exceeding safe temperature limits. ls the size of locomotive motors is largely determined by their ability to adiate heat, the use of forced ventilation naturally follows as the next step n advance.

143. Standard Westinghouse direct-current commutating-pole railway motors

Motor type No.	H.p. at 600 volts	No. of motors	Type of control	Weight of double end control	Weight of motor with gears	Total weight of equipment
508-A	25	2	K-63-BR	769	1,035	2,869
		4	K-35-GR$_2$	1,228		5,428
508-C	25	2	K-63-BR	769	1,100	2,999
		4	K-35-GR$_2$	1,228		5,688
514-A	40	2	K-63-BR	925	1,700	4,365
		4	H.L.	1,827		8,707
514-C	40	2	K-63-BR	925	1,770	4,505
		4	H.L.	1,827		8,987
532-B	50	2	H.L.	1,528	2,325	6,208
		4	H.L.	1,888		11,248
306-CV	65	2	H.L.	1,736	2,700	7,166
		4	H.L.	2,108		12,968
547-C	80	2	H.L.	1,800	3,175	8,190
		4	H.L.	2,650		15,430
548-C	100	2	H.L.	1,856	3,175	8,246
		4	H.L.	2,719		15,499
333-V	125	2	H.L.	1,941	3,850	9,641
		4	H.L.	2,835		18,235
557-A	140	2	H.L.	2,187	4,050	10,287
		4	H.L.	3,166		19,366
567-A	165	2	H.L.	2,633	4,900	12,433
		4	H.L.			
577-A	190	2	H.L.	2,750	5,650	25,350
		4	H.L.			
			600–1,200 Volt Motors (Full speed on 600 Volts) Without Dynamotor			
306-CV	65	4	H.L.	3,037	2,700	13,897
547-C	80	4	H.L.	3,451	3,175	16,231
548-C	100	4	H.L.	3,651	3,175	16,431
333-V	125	4	H.L.	3,909	3,850	19,309
557	140	*4	H.L.	4,000	4,050	20,200
567	165	*4	H.L.	3,600	4,900	23,200
577	190	4	H.L.	3,800	5,650	26,400
			750–1,500 Volt Motors			
Motor type No.	H.p. at 750 volts	No. of motors	Type of control	Weight of double end control	Weight of motor with gears	Total weight of equipment
545-C	85	4	H.L.	3,472	3,175	16,172
334-V	120	4	H.L.	4,100	3,850	19,500
567-A	200	*4	H.L.	3,600	4,900	23,200
577-A	230	*4	H.L.	4,264	5,650	26,864

* Half speed on 600 and 750 volts.

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144. Alternating-current single-phase railway motors

Type No.	H.p.	No. of motors per equipment	Type of control	Weight of control (lb.)	Weight of motor gear, gear case, axle bearings and axle caps (lb.)	Weight of drive details (lb.)	Service
135-B	75	4	Unit switch	8,525	4,500 lb.		Motor car
132-A	100	4	Unit switch	9,670	5,300 lb.		Motor car
148-A	125	4	Unit swtich	9,300	6,100 lb.		Motor car
409-B	175	4	Unit switch	15,400	6,900 lb.	800 lb.	Motor car
412	225	2	Unit switch	11,500	7,200 lb.		Motor car

RAILWAY-MOTOR CONTROL

145. Classification. There are two general types of control used with direct-current series-wound railway motors, namely: drum control and multiple-unit control. With each of these types there are two systems which may be used, these being known as the straight rheostatic control system and the series-parallel control system.

146. With the straight rheostatic system of acceleration the motors are connected permanently in series or parallel according to the arrangement desired, and the full starting resistance is connected in series with the motors. This resistance is then notched out of circuit, step by step, until full potential is applied to the motors. This arrangement is used for single-motor equipments, two-motor equipments on double voltage (two 600-volt motors insulated to withstand 1,200 volts on a 1,200 volt circuit), and for slow-speed industrial cars or mining locomotives of small capacities.

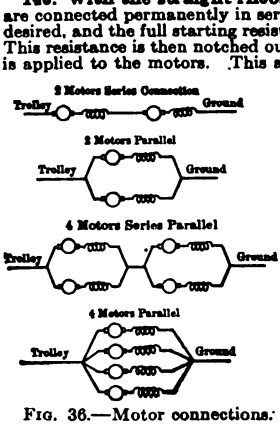


FIG. 36.—Motor connections.

147. The chief advantages of a series-parallel control system are that two running speeds are obtained, and that economy is effected during acceleration. The motors or groups of motors (Fig. 36) are first connected in series with the full starting resistance in the circuit. This resistance is then notched out of the circuit, step by step, until full-line potential is applied to the motors or groups of motors in series. A portion of the resistance is next re-introduced in the circuit, and the motors or groups of motors are connected in parallel. Finally, the resistance is cut out of the circuit step by step until full-line potential is across the motors or groups of motors in parallel.

148. Three methods of transition from series to parallel are in use, these being known as the shunting or "K" method, the bridging method, and the open circuit or "L" method. Shunting transition derives its name from the fact that in changing from series to parallel, resistance is re-introduced into the circuit, then one motor or group of motors is short-circuited (shunted) and is subsequently thrown into parallel with the other. In the bridging transition, after the motors are running in full series with no resistance in circuit, a portion of the main resistance is thrown in parallel with each of the motors or groups of motors. Following this, the circuit between the motors is opened in such a way as to leave resistance in series with each of the motors or groups of motors, and the latter in parallel. The open-circuit transition derives its name from the method of opening the power circuit entirely before changing the connections.

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149. The distinctive feature of cylinder (drum) control is that the various electrical connections are made and broken manually, by means of a and controller. This consists of an upright cylinder upon which are mounted the contacts and against which stationary fingers press. When the cylinder is rotated (by means of a handle) the contacts connect the proper ngers to form the required electrical connections.

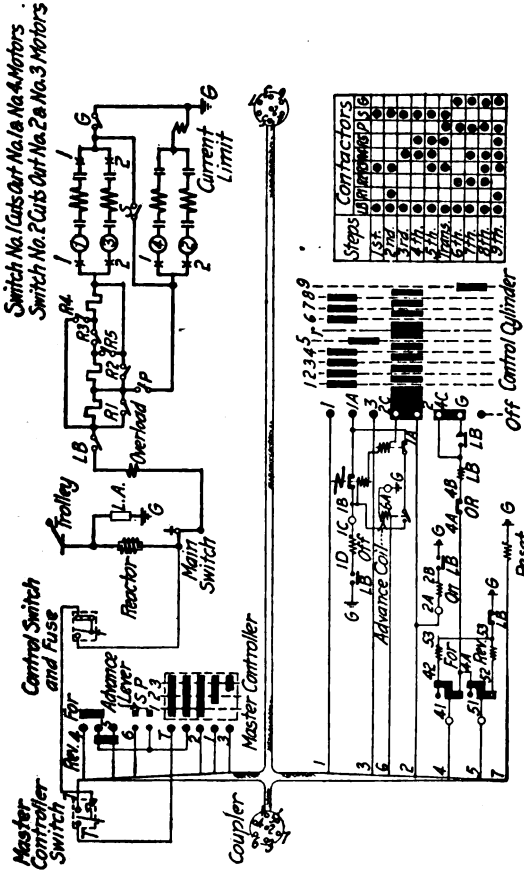


FIG. 37.—Connections of General Electric type PC-5 controller, with four motors

150. Cylinder (drum) controllers are classified as follows: Type "*K*" controllers are of the series-parallel type and include the feature of shunting and short-circuiting one motor or group of motors, when changing from series to parallel connection.

Type "*L*" controllers are of the series-parallel type, but completely open the power circuit during transition from series to parallel connection.

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Type "*R*" Controllers are of the rheostatic type and are designed to control one or more motors by means of resistance only. Certain of these controllers are arranged so that the motors may be grouped either in series or in parallel at the option of the operator, but as this must be accomplished by throwing a separate lever, these controllers are not used as series-parallel controllers and their field is limited.

Type "*B*" controllers may be either of the rheostatic or the series-parallel types, but they differ from the ordinary rheostatic or series-parallel controllers by having the contacts arranged so that if desired, the power may be cut off, the motors reversed and then short-circuited through a variable resistance, the motors thus acting as series generators. Beside the braking effect of the motors acting as generators, use is sometimes made of magnetic rail brakes or axle brakes, the coils of these magnetic brakes being in series with the short-circuited generators.

151. Capacity of drum controllers. Two ratings are given to drum controllers, conforming to the double ratings presented by the A. I. E. E. for railway motors (see Par. **121** and **122**). That is, the capacity of drum controllers is defined by specifying the 1-hr. rating and also the continuous rating in amperes at three-fourths voltage of the largest motors with which the controller can be used. It is necessary therefore in selecting controllers for a given motor equipment to note that neither the hourly rating in horsepower nor the continuous rating in amperes is exceeded. It is further necessary to define the number of motors the control is arranged for and also the maximum voltage of the circuit on which it can be used.

152. Standard series-parallel controllers—600 volts

Type	No. of motors	Capacity		No. of points		Maximum potential, volts	Remarks
		H.p.	Amp.	Series	Parallel		
K-35	4	65	60	5	3	750	.....
K-36	2	70	66	4	4	750	.....
K-51	2	70	66	5	4	750	For tapped-field motors
K-63	2	40	38	4	3	750	.....
K-64	4	110	105	6	4	750	.....

153. Line circuit breakers with drum controllers. In order to eliminate the severe arcing from controller fingers when the main circuit is broken, an attachment is fitted to the lower end of the main cylinder shaft for the purpose of closing and opening the main circuit breaker. This circuit breaker with an overload relay is enclosed in a sheet metal box and located under the car body. The line breaker used for this purpose is magnetically operated and is provided with renewable contact tips and a powerful magnetic blowout coil with large arc chute. The attachment in the controller is essentially a ratchet switch which makes contact and closes the circuit breaker when the control handle is turned to the first point and remains closed throughout all succeeding positions of the operating handle. When the controller is notched back in the "off" direction the ratchet switch opens and de-energizes the line breaker which opens the main circuit regardless of the position of the operating handle. Thus the current is cut off before the control fingers break contact. To close the line breaker again the operating handle must be turned completely off and brought back on the first point as before. In case of overloads the overload relay operates and opens the line breaker. In this equipment the line breaker takes the place of the hand-operated breaker which is usually located in the vestibule.

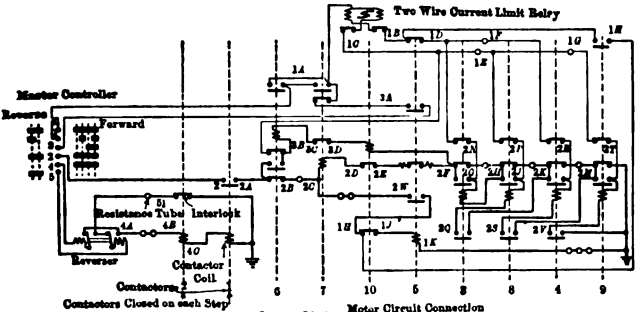
154. Multiple-unit control is a term originally applied to a control system which was designed to permit a train of motor cars, when coupled in any combination, to be operated as a single unit from either end of any car in the train. To secure this result several methods have been adopted. Fundamentally the methods are essentially identical but the means employed have differed. That is, the control systems for each car may be considered in two parts, one consisting of apparatus which makes the main connections, or motor controller, and the other part consisting of apparatus

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which governs the operation of the motor controller, that is, a master controller. There are three ways in which this has been done as described in Par. **148.**

155. General Electric contactor control employs magnetically-operated contactors or circuit breakers which are opened and closed in proper sequence by means of train wires which are energized through a master controller.

156. The master control (Par. **155**) Fig. 38 comprises those parts which switch the control current operating the motor-control apparatus. The master controller is operated by hand, and is located in the vestibule at either end of the car. The motor control is local to each car, and current for this circuit is taken directly from the trolley or third-rail through the contactors, starting resistance and reverser to the motors, thence to the ground. Where it is necessary to operate with a gap in the third-rail system, it is sometimes customary to install a train line so that any car may supply the motor current for the other cars of the train.



Steps	Contactors								
	1	2	3	4	5	6	7	8	9	10
1st	•	•					•			
2nd	•	•	•				•			
3rd	•	•	•				•	•		
4th	•	•	•	•			•	•		
5th	•	•	•	•			•	•	•	
6th	•	•			•					
7th Pre.	•	•			•	•				•
7th Fin.	•	•				•				•
8th	•	•	•			•				•
9th	•	•	•			•		•		•
10th	•	•	•	•		•		•		•
11th	•	•	•	•		•		•	•	•

FIG. 38.—Sprague General Electric contactor control.

The master control includes train wires made continuous throughout the train by means of couplers between the cars. On each car the operating coils of the motor control are connected to this train line through a cut-out switch, these train wires being energized in proper sequence by the hand-operated master controller on the platform. Current for the master control is taken directly from the trolley or third-rail through the master controller, which is being operated by the motorman, to the train-line, and thus to the operating coils of the contactors forming the motor control on all cars of the train.

157. The master controller (Par. **155**) is similar in design to the original cylinder controller in that it contains a movable cylinder and stationary contact fingers through which current is supplied in proper sequence to the different wires of the train line, for energising the operating coils of the mo-

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control. The value of the current required is very small, not exceeding 2.5 amp. for each car in the train. The master controller is provided with two handles, one for operating and one for reversing the train movement.

The operating handle is provided with a button which must be kept down except when the handle of the controller is in the off position, as releasing this button permits an auxiliary circuit to open, cutting off the supply of current to the master controller, and thus de-energizing the train-line and opening up the motor-control apparatus. This button is intended to serve as a safety appliance in case of physical failure of the motorman.

The reverser handle is connected to a separate cylinder which establishes control connections for throwing the electrically operated reverser either forward or reverse position when the master-controller handle is on the off point. The operating circuit for the reverser is so interlocked that unless the reverser itself corresponds to the direction of the movement indicated by the reverser handle of the master controller, the line contactors on that car cannot be energized.

158. The contactor (Par. **155**) is a switch operated by solenoid coils and each contactor may be considered as the equivalent of a finger and its corresponding cylinder segment in the hand-operated "*K*"-type controller. It consists of an iron magnet frame with an operating coil and two main contacts, one fixed and the other directly connected to the movable finger. These main contacts open and close in a moulded-insulation arc chute provided with a powerful magnetic blowout. Interlocks are provided for making the necessary connections in control circuits to ensure proper sequence in operating the different contactors.

All of the contactors are mounted in a box placed beneath the car, this box being provided with a sheet-steel cover lined with insulating material.

159. The reverser (Par. **155**) is a switch, the movable part of which is a rocker arm operated by two electromagnets working in opposition. The coils receive their energy from the master controller through the train-line, and the connections are such that only one coil can be operated at a time. Leads from the motors are connected to the main reverser fingers, and by means of copper bars on the rocker arm, the proper relations of armature and field windings are established for obtaining forward or backward motion of the car. Also see Par. **178.**

160. Circuit couplers between cars (Par. **155**) are so designed as to give a corresponding connection of train wires, this being secured by means of proper mechanical design of plug and sockets, it being rendered impossible to insert the plug in the socket improperly.

161. Automatic multiple-unit control. Sprague General Electric automatic (Par. **155**) provides for the acceleration of the train at a predetermined value of current in the motor, this feature being provided without preventing the manual operation of the master controller at less than the predetermined current if desired.

The operation of the contactors is controlled from the master controller, but is governed by a notching or current-limit relay in the motor circuit, so that the accelerating current of the motors is substantially constant.

This is accomplished by having small auxiliary interlocking switches on certain of the contactors, the movement of each connecting the operating coil of the succeeding contactor to the control circuit. The contactors are energized under all conditions in a definite succession, starting with the motors in series and all resistance in circuit; the resistance is subsequently cut out step by step; the motors are then connected in parallel with all resistance in circuit, and the resistance again cut out step by step. The progression can be arrested at any point, however, by the master controller, and is never carried beyond the point indicated by the position of the master controller. The rate of the progression is governed by the current-limit relay, so that the advance cannot be made at a rate so rapid that the current in the motors will exceed the prescribed limit. One of these relays is provided with each car equipment, so that while the contactors on each car of a train are controlled from the master controller in use for the application and removal of power, the rate of progression through the successive steps is limited by the relay on each car independently, according to the adjustment and current requirements of that particular car.

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162. The control for 1,200-volt, 1,500-volt, 2,400-volt and 3,000-volt car equipments (Par. 155) is essentially the same as that described for 600-volt service except that two motors are usually connected permanently in series. Series-parallel connection of the two groups of motors provides for half speed and full speed, but when full speed is desired on 600-volt supply, a commutating switch is provided with the 1,200-volt equipments, thus changing the motors from two in series to all in multiple. Usually, however, two motors remain permanently in series, and provide half speed when 1,200-volt cars run over terminal tracks supplied with energy at 600 volts. A dynamotor or motor-generator set run from the trolley supplies current at low voltage for actuating the switches. The air compressor and heaters operate direct from the trolley circuit.

163. Protection against failure of power (Par. 155). Another automatic protection for individual cars is provided by a second or **potential relay**, which has its coil connected to the lead from the collecting shoes of the respective car. The contacts are so connected in the contactor circuits, that in case of failure of power to any car (such as would be caused by passing over a dead section of rail), this relay is de-energized and causes the control circuits on that car to be thrown back to the series position with resistance in circuit. When power is re-applied the control progresses step by step to its former advanced position. This method prevents any surging or overloading in such contingencies.

164. Train-wire circuits (Par. 155). There are five circuits leading from the master controller, and five corresponding train wires. The five circuits comprise one for forward direction, one for reverse, one each for series and parallel, and the fifth for controlling the acceleration. When the master controller is moved to its first forward point a direction wire is energized which throws the reverser to its forward position, if it is not already so thrown. The reverser is electrically interlocked so that it cannot be manipulated when the motors are taking current.

The operating circuit is so arranged that unless the reverse is thrown for the direction of car movement indicated by the master-controller handle, the contactors and motors on that particular car are inoperative. When the reverser has moved to the proper position, connections are made by it from the direction wire, through the forward reverser-operating coil, to the coils of the contactors which control the main or trolley leads to the motors.

165. General electric cam control. This is a later design of multiple-unit control than the contactor type (Par. 155) and is a more direct application of the principle of the drum controllers. In certain features it resembles both the drum controllers and also the contactor control. That is, instead of the main controller shaft of the drum controller with segments mounted thereon and turned by hand, there is substituted in the new control a cam shaft which is operated by means of compressed air. This cam shaft operates the contactors by means of cams. It has been possible with this design to assemble the contactors, reverser, line breaker relays, etc., in one box beneath the car body. The electric control circuits are greatly simplified and positive serial action of the contactors has been obtained without electrical interlocks. It also weighs less than the older type of contactor control.

166. Air-operated line circuit breaker and reverser. The line breaker and reverser (Par. 165) are provided with individual air cylinders and magnet valves. These magnet valves control the air inlets and outlets of cylinders which in turn close the line breaker and operate the reverser. The operation of these valves is governed through train wires which are energized through the master controller.

167. Air-operated cam shaft. The contactors (Par. 165) instead of having individual magnet valves and air cylinders similar to the line breaker and reverser are all operated by means of cams mounted on a horizontal shaft which carries a pinion at one end. This pinion engages with a rack as shown in Fig. 39, which is moved back and forth by a double-acting air piston. Air is admitted or released from either end of the air cylinder by means of magnet valves which are energized through the master controller and train circuit.

168. Controller air cylinder. The ends of the controller air cylinder (Par. 165) are fitted with magnet valves and are designated as the "on" and "off" ends. The "on" end is the end of the cylinder at which air is

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admitted to turn the controller "on" and likewise the "off" end is the end at which air is admitted to turn the controller off. When the magnet valves are de-energized the normal position of the "on" valve is closed to the reservoir and open to the exhaust. The normal position of the "off" valve when the magnet valve is de-energized is just the reverse, closed to the exhaust and open to the reservoir. When the car is stopped the magnet

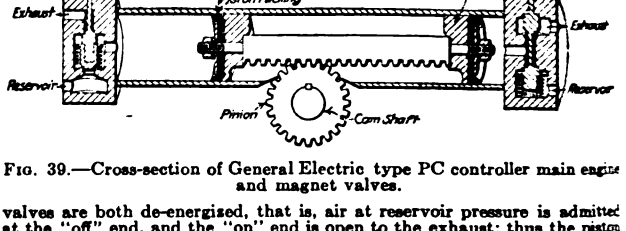


FIG. 39.—Cross-section of General Electric type PC controller main engine and magnet valves.

valves are both de-energized, that is, air at reservoir pressure is admitted at the "off" end, and the "on" end is open to the exhaust; thus the piston is forced in the direction which turns the motor controller "off," i.e., toward the "on" end. When the master controller is turned on and the reverser throws, the line breaker closes and both the "on" and "off" magnet valves are energized, that is, air is admitted to the "on" side of the piston and exhausted from the "off" side and the rack revolves the cam shaft

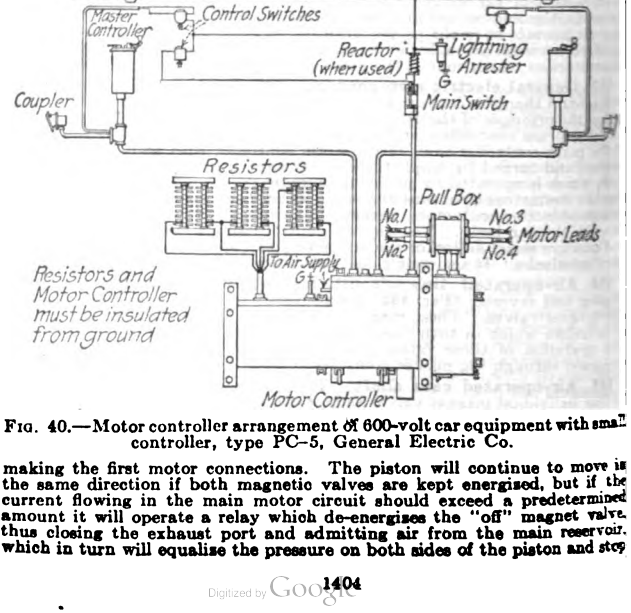


FIG. 40.—Motor controller arrangement of 600-volt car equipment with small controller, type PC–5, General Electric Co.

making the first motor connections. The piston will continue to move in the same direction if both magnetic valves are kept energized, but if the current flowing in the main motor circuit should exceed a predetermined amount it will operate a relay which de-energizes the "off" magnet valve, thus closing the exhaust port and admitting air from the main reservoir, which in turn will equalize the pressure on both sides of the piston and stop

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its movement. When the current in the main circuit falls below this predetermined value the "off" magnet valve is again energised and the motor controller moves on to the next point.

169. Master controller (Par. 165). There are three points on the master controller; the first point gives the first point series, the second all series positions and the third all parallel positions. As shown in Fig. 40 there are five steps in series on the motor controller, all of which except the first are obtained automatically by moving the master controller to the second notch. Likewise there are four steps in parallel on the motor controller, all of which are obtained by moving the master controller to the third point. The progression from one point to the next will only take place as fast as the notching relay, which energizes the "off" magnet valve, operates. The cam control is, therefore, inherently an automatic control which secures constant acceleration, but is simpler than non-automatic control with the contactor type.

Advance lever. A third handle is located on the master controller (Par. 169) cap plate. This handle is known as the advance lever and is used to advance the motor controller point by point if in emergencies the car will not accelerate at the current for which the notching relay is set.

170. Overload relay. An overload relay is part of these equipments and its function is to trip the line breaker in case of overloads. In turning off the power the master controller is usually turned off faster than the motor controller can follow. When the master controller is in the off position it de-energizes the magnet valve on the line breaker and opens the circuit at this point. The cam-operated contactors are, however, equipped with magnetic blowout coils and arc chutes so that current can be interrupted at these points also.

171. The Westinghouse unit-switch system of control is arranged for use either on alternating-current or direct-current circuits, and for capacities varying from the smallest double-motor equipments to those of the largest locomotives. The control circuits for an alternating-current installation are usually energised from a storage battery, while those for a direct-current installation may either be operated from a storage battery or by the use of energy from the line. When the latter is used for the control, a resistance is inserted between the trolley and the ground whenever the master controller is in one of the operating positions; taps leading from this control resistor provide various low voltages at which the control circuits may be energised.

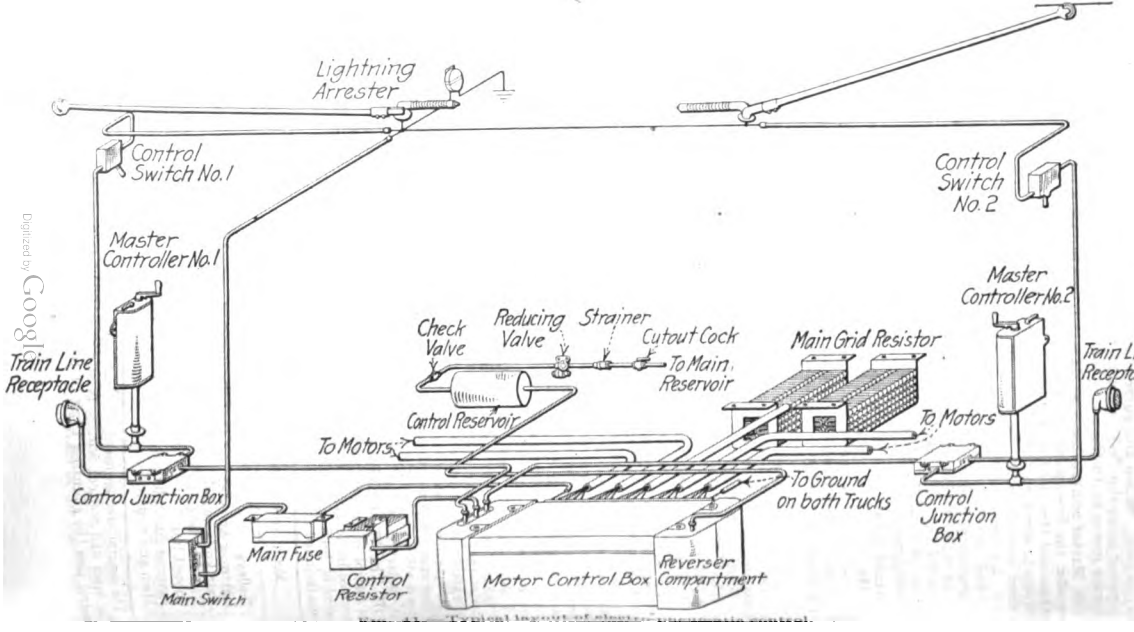
Westinghouse unit-switch control equipments are classified according to whether they are arranged for hand (manual) or automatic acceleration, whether they employ energy from the line or a battery for control, and whether they have any other distinctive features, such as field control or multiple operation with General Electric Co.'s. type "*M*" control. Some of these standard designations are as follows: *HB, AB, HLF, AL, ALM*, etc. Thus it will be noted that "*H*" signifies hand acceleration, "*A*" automatic, "*B*" battery control, "*L*" line control, "*F*" field control of motors, etc.

172. The Westinghouse "HL" system of control is widely used for the control of direct-current motors on city and interurban cars and is described in detail in Par. 173 to 183. A standard car equipment for the control of 4–65 h.p. 600-volt motors arranged for double-end operation in trains included the following parts:

Main circuit apparatus	Control apparatus
2 Trolleys	2 Master controllers
1 Lightning arrester	2 Control and reset switches
1 Main knife switch	1 Control resistor
1 Main fuse box	2 Train line junction boxes
1 Control box	2 Train line receptacles
1 Reverser (included in control box)	1 Train line jumper
1 Main grid resistor	1 Set of pneumatic details

The general arrangement of this apparatus on the car is shown in Fig. 41. The main and control wiring is shown clearly in Fig. 42. This system of control uses the shunting type of transition from series to parallel.

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173. The main switch (Par. 172) is arranged for mounting underneath the car and is enclosed in a box, which protects it from the weather and insures against accidental contact.

174. The main fuse box (Par. 172) is of the magnetic blow-out, copper-ribbon type, arranged for mounting under the car. The fuse gives an additional safeguard in series with the circuit-breaking switches which ordinarily open the circuit in case of overload or short circuit.

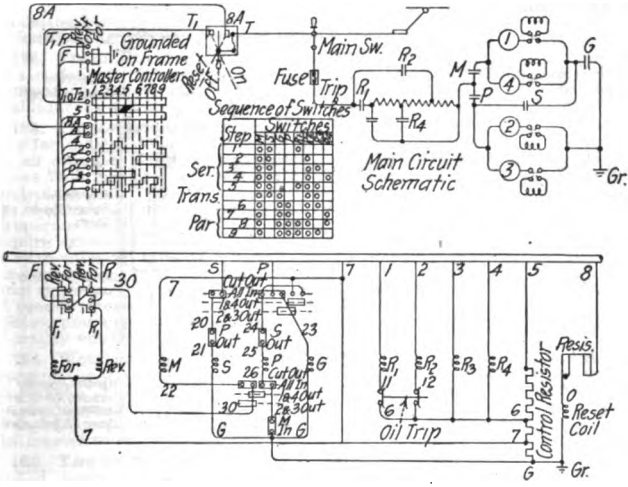


FIG. 42.—Schematic diagram of control box, with four motors.

175. Control box (Par. 172). The various main circuit connections are made by means of a number of independent switches known as unit switches, each provided with a strong magnetic blowout and normally held open by a powerful spring. Each switch is closed when desired, by compressed air acting on a piston. This action forces the switch jaws together against the spring pressure, the force being sufficient not only to compress the spring but also to apply a heavy pressure at the switch jaws. The air is admitted to or exhausted from the cylinder through a valve which is operated by means of an electro-magnet in the control circuit. The control box includes the assembly of a number of these unit switches and blowout coils, reverser, cut-out switches, and overload trip relay in a common frame, completely enclosed by removable sheet-steel covers lined with asbestos. A cross-section view of the control box, indicating the construction and operation of the unit switches is shown in Fig. 43.

176. Interlocks are provided to make the necessary changes in the control circuits in order to secure the proper sequence of switches and to safeguard against improper operation. These interlocks consist of copper contacts, mounted on an insulated base, which is mechanically connected to the movable switch element. Stationary fingers press against this block and make the necessary control-circuit connections in the "IN" or "OUT" position of the switch.

177. Line switch (Par. 172). On equipments where it is necessary to have an increased number of switches to secure a larger capacity, two of the switches are mounted in a separate frame with the overload trip. This assembly constitutes what is termed a "line" switch. The overload tri-

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relay includes a series coil connected directly in the trolley circuit. Within this coil is mounted a movable plunger to which are attached insulated metal discs connected in the control circuit. Excessive current through the coil moves the plunger and opens the control circuits of certain switches which cut off the power. The plunger is held in the normal position by gravity assisted by a spring, but when actuated is latched in the open position and must be released manually or by energizing a reset coil from the control and reset switch in the cab. Calibration is accomplished by an adjustment of the air gap.

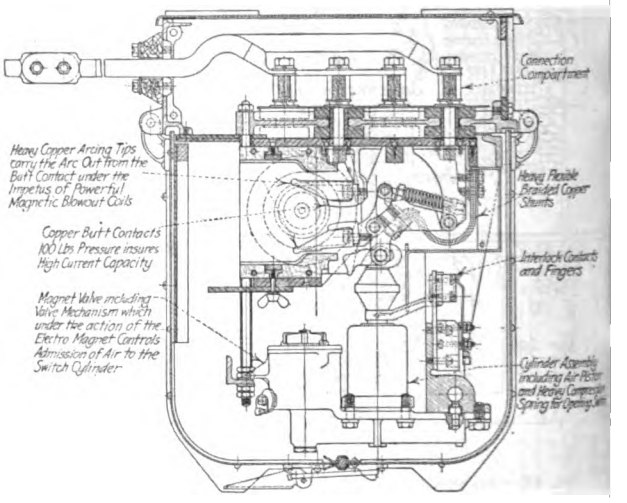


FIG. 43.—Electro-pneumatic switch unit.

178. Reverser (Par. 172). The direction of rotation of the motor is changed by reversing the main fields. The reverser consists of the necessary number of main circuit fingers mounted on a stationary base, and arranged to press against contacts carried on a movable drum. The drum with its contacts is moved to the forward or to the reverse position by one or the other of two pneumatic cylinders, closely resembling those in the control box, except that no springs are used. Each cylinder is controlled by a magnet valve similar to those in the control box. The reverser is mounted on one end plate of the control box (Par. 175), which greatly simplifies the main circuit connections and the mounting of the apparatus.

179. The master controller (Par. 172) is a small drum-type controller which governs the application of power to the control circuits. Although much smaller in size, this controller is similar in construction to the usual main drum controller, having one handle governing the direction of motion and another governing the acceleration, the two handles being mutually interlocked. Energy for the control is obtained from the line by taking low-voltage taps from a resistor connected from line to ground. This resistor is connected to the line through high-voltage fingers and contacts on the master controller and a fused control switch. A magnetic blowout coil is provided for rupturing the arc at the high-voltage fingers. In operation the controller connects the trolley potential to the control resistor and also regulates the connections of the low-voltage control circuits to the various operating coils.

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180. The control resistor (Par. 172) consists of a number of resistance nits mounted in a common frame with a sheet-iron cover. Each unit is ade by insulating a slotted steel ribbon with mica and enclosing this insu- ated ribbon in a sheet-iron scabbard. The scabbard is firmly pressed against he mica insulation, and being waterproof renders the resistor especially uitable for railway service.

181. The control junction boxes (Par. 172) are provided for making onvenient control-circuit connections between the master controller, the rain line receptacles and other control apparatus. Each box contains an nsulating base, provided with a number of terminals, and has a hinged lid o facilitate installation and inspection.

182. Train line receptacles are provided when multiple operation of ars is desired. These receptacles together with the necessary **train line umpers** complete the control circuits between adjacent cars, allowing imultaneous operation of all equipments so connected.

183. Pneumatic details (Par. 172) for supplying air at the proper pres- ure for the control, are furnished with each equipment. These consist of n air strainer, a reducing valve (when the main reservoir air pressure is bove 75 lb.), a check valve and a control reservoir. The check valve and ontrol reservoir permit the operation of the control system in event of fail- re of the main air supply, the control reservoir having sufficient air capacity o operate the control a great number of times. Local conditions sometimes equire extensive control operation even though the main air supply fails; n such cases an emergency control reservoir is employed. The use of air or braking purposes has proven that very little trouble may be expected rom this source if the piping is properly arranged and the reservoirs drained t proper intervals. The use of air for operating switches insures a heavy ontact pressure at the switch jaws, which pressure is, of course, independent f trolley voltage.

184. Westinghouse type "AL" control. Where service conditions arrant the use of automatic acceleration a modified type of equipment is mployed. The operation of the switches which commutate the main esistor circuits and establish the series or parallel connection of the motors Par. 172) is governed by a sequence switch which in turn is operated from he master controller under the control of a limit relay.

185. The sequence switch (Par. 184) is essentially an electrically con- rolled, pneumatically operated drum which carries contacts arranged for nergising the valve magnet coils of the control box. It consists of two air

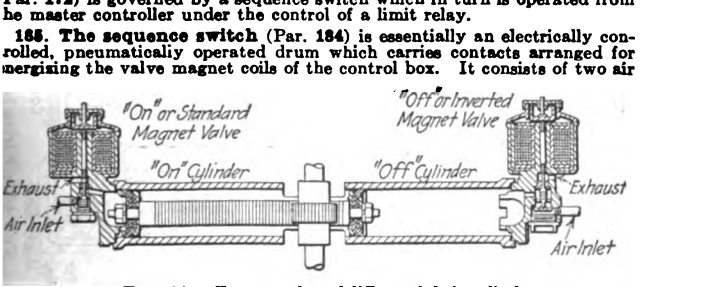


FIG. 44.—Cross-section of differential air cylinders.

ylinders with the pistons connected by a rack which transmits the move- nent of the pistons through bevel gears to the drum carrying the contacts. Compressed air is admitted or released from the cylinders by means of a nagnet valve at each cylinder. The magnet valves are similar in general onstruction to those in the control box, but the operation of one valve is lifferent in that when this magnet valve coil is energized, air is released rom the cylinder and when the coil is de-energized, air is admitted; this is alled the "off" magnet valve. The other valve admits air to its cylinder hen the coil is energized and releases air when the coil is de-energized; his is called the "on" magnet valve and is the same in operation as the valves f the control box. If both magnet valves are energized simultaneously, novement of the drum results since air is admitted to one cylinder and

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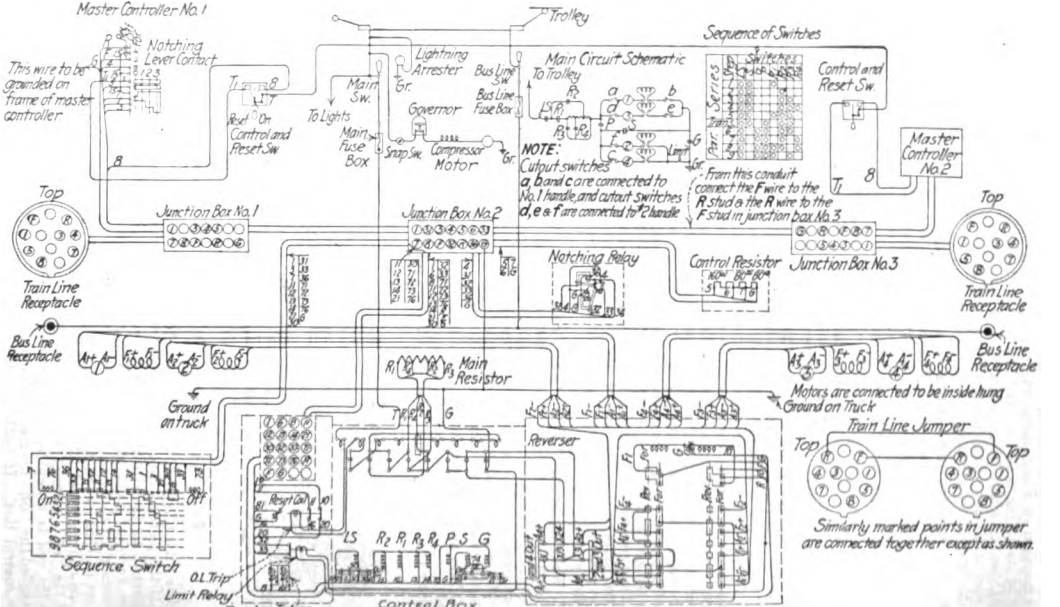


FIG. 45.—Wiring layout for multiple-unit electro-pneumatic control.

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released from the other. With neither magnet energized, the air in the "on" valve magnet cylinder is at atmospheric pressure, while that in the "off" valve magnet cylinder is at reservoir pressure, thus holding the pistons and drum in the "off" position. Energising the "on" magnet balances the pressure on the two pistons but causes no movement. Thus to move the

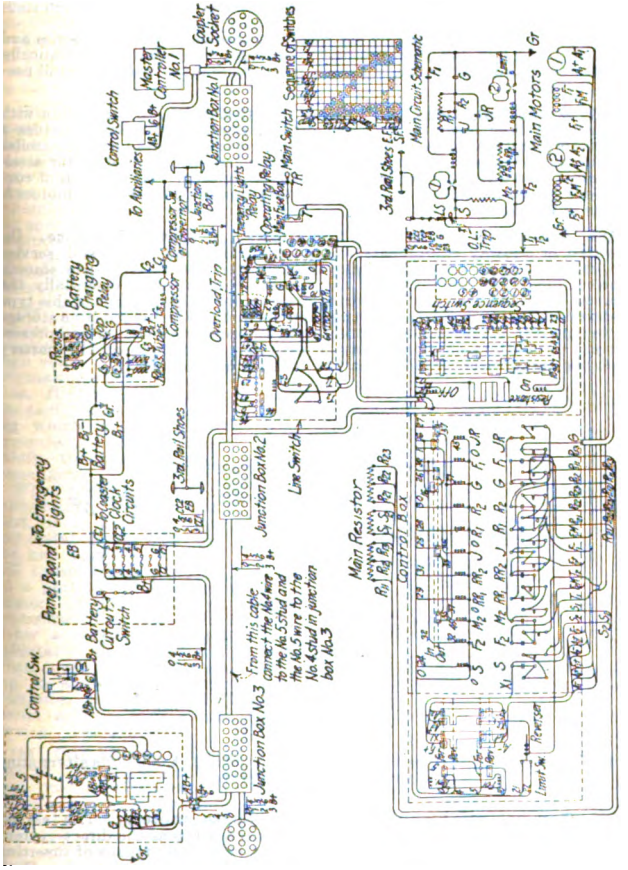


FIG. 46.—Schematic diagram of multiple-unit control, 600 volts, direct current.

piston and drum in successive steps, it is only necessary to energise the "on" magnet from the supply circuit and the "off" magnet through the limit relay contacts. The general construction of the cylinder, pistons and valves is shown in Fig. 44.

186. The limit relay (Par. 184) is a solenoid type with a series coil connected directly in the main motor circuit. The relay armature carries con-

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tacts, which are connected in the control circuit to the sequence switch. The relay armature lifts when the main motor current reaches a certain predetermined value, thus interrupting the control current to the "off" valve magnet and halting the progression of the drum. As the motor speed increases, the current will fall until a value is reached where the limit relay plunger will drop again, closing the operating circuit to the sequence switch. This performance is repeated until the control has reached the notch indicated on the master controller.

Three points are provided on the master controller—switching, series and parallel. The first one gives the first point series; the second automatically progresses the control to the full series position, and the last to the full parallel position.

187. A notching relay (Par. 184) is included which, in connection with a small notching lever incorporated in the master controller, provides a means for obtaining step-by-step notching on heavy grades or under similar conditions of operation where the current required by the motors for acceleration is above that for which the limit relay is set. The diagram of connections for an automatic equipment of this type for four 40-h.p. motors is shown in Fig. 45.

186. Automatic equipments for subway or elevated service. On elevated or subway equipments where long trains and high-speed service are common, it is usual to employ bridging transition to insure smooth acceleration. The operation of the control equipment is essentially the same as described above. The wiring diagram for an equipment of this type is shown in Fig. 46. Energy for the control circuits is provided by a storage battery, which is charged by connecting it in series with the air-compressor circuit. A battery-charging relay is provided to disconnect the battery from the compressor circuit when the latter is not running.

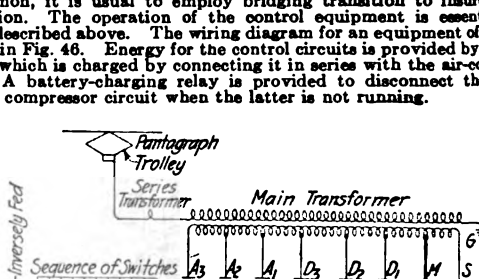


FIG. 47.—Schematic diagram of main circuit control, 11,000 volts alternating current, with two motors.

189. Tap-potential control of single-phase motors. The single-phase motor is essentially the same in its characteristics as the direct-current series-wound motor, and can be started at low voltage by means of insertion of series resistance according to the direct-current standard method. With alternating-current supply, however, it is possible to obtain fractional voltage without sacrificing efficiency, as the step-down transformer forming part of the alternating-current car equipment and be constructed with taps so that it will furnish fractional voltage without the necessity of introducing starting resistance. The universal method of starting single-phase motors is, therefore, by the so-called tap-potential control, and the function of the

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ontrol, whether it be hand-operated "K" type or multiple unit, is to con-ect the motor terminals successively to transformer taps of increasing poten-al while starting.

190. The hand-operated control of single-phase motors is identical ith the type "K" controller used with direct-current motors, except that dvantage is taken of the fact that alternating-current arcs of considerable se can be broken in the air without the aid of the magnetic blowout. Where he cars are to be operated from both alternating-current and direct-current rolley with the same equipment, the hand-operated control is provided ith magnetic blowout for direct-current operation, using the same controller ithout the magnetic blowout for alternating-current operation, unless the notor equipment be of large capacity.

191. Control of single-phase motors for combined alternating-urrent and direct-current service. The control of single-phase notor is effected by connecting the motor terminals to transformer taps of ncreasing potential in order to vary the speed, while reversal is effected by reversing the series field-winding connections, thus calling for practically the ame combinations as demanded in direct-current series motor control. lternating-current series motors are wound for low potentials not exceed-ng approximately 300 volts per motor, and such motors in order to meet the xactions of commercial operation must sometimes be adapted to run with 00-volt direct-current. In such cases it requires some additional features control to perform this double service of alternating-current and direct-urrent control.

192. The Westinghouse alternating-current motor control is very imilar to the direct-current control. Pantagraph trolleys are ordinarily mployed because of the igh voltages common for lternating-current opera-ion. High-potential wires re enclosed in metal tub-ng which is thoroughly rounded in order to insure afety to operator and assengers.

When passing from one ransformer tap to the ext, it is evident that ny metal contact bridging he gap between the two ill cause a short circuit n a portion of the trans-rmer. It is therefore ecessary to introduce ither a resistance or an nductance in the circuit hen passing from one ap to another. An in-uctance, termed a *re-ctive coil*, is most frequently used in both locomotive and motor-car ervice. See Fig. 48.

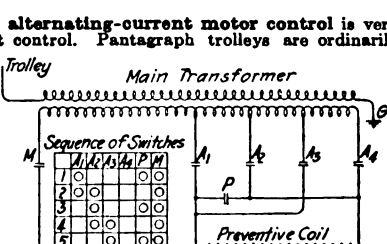


FIG. 48.—Schematic diagram of main circuit control, alternating current, with two motors.

193. Combined alternating-current and direct-current equip-ents. At times existing conditions may require the operation of an equip-ent on both alternating-current and direct-current systems, an example f this being the equipments of the N. Y., N. H. & H. R. R. Co. which enters he Grand Central Terminal in New York City. No change is required in the ngle-phase motor for direct-current operation, but since the control is ecessarily of a different character, some means must be provided for re-ar-anging circuits. This is usually accomplished by means of a drum type of hange-over switch, but if heavy currents are to be handled, individual knife witches are employed. The control apparatus used with a combination al-rnating-current-direct-current equipment is, in general, more complicated han equipments for straight alternating-current or straight direct-current peration.

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194. Number of starting points (Par. 196). Owing to the fact that the alternating-current motor characteristic is more drooping than that of the direct-current series-wound motor, fewer starting points are required for this type of control. Since each point on the controller constitutes a running point at full efficiency, it is not necessary to use series-parallel connection of motors as is done in direct-current equipments. A total of seven notches is usually all that is required.

195. Multiple-unit control equipments for single-phase motors differ somewhat from direct-current equipments in the general plan of operation. This difference is confined chiefly to the main circuits and main-circuit apparatus. The high-tension current passes from the overhead collector through an oil circuit-breaker, to a transformer. Low voltage currents are fed to the main motors through a group of unit switches, which can be arranged for automatic or non-automatic acceleration. Fig. 6 shows the connections for a typical type "*AB*," 11,000-volt single-phase equipment.

TYPES OF RAILWAY MOTORS

196. Direct-current series-wound motor. Wound for potentials of from 500 to 1,200 volts is the standard railway motor. Motors of from 30 to 600 volts are used in and around large cities, 1,200-volt motors being adopted on interurban electrified lines. Armature and field windings are connected in series and the use of motors of the commutating pole type is increasing. All motors designed for street, interurban and rapid transit or or train service have four field poles, the structure being entirely enclosed with hand hole covers making it waterproof. Such motors transmit power by single-reduction gear, motors being suspended at one end upon the car axle and spring suspended at the other end.

For locomotive work, the General Electric Company has brought out a two-pole gearless motor, which design is also adapted for high-speed single-car service calling for large motor outputs. The two-pole series motor is especially adapted to very high speed service; it minimizes cost of repairs and operates with decreased noise and greatly increased efficiency for express service. For further description of gearless motors see locomotives (Par. 270).

197. The single-phase series motor has been developed along several lines of which the series-wound compensated motor is the one most generally used in the United States. The single-phase motor differs from the direct-current series-wound motor in having two fields, the series or energizing field and the **compensating field.** The office of the latter is to compensate for or neutralize the inductance of the armature produced by the alternating current therein. Compensation may be the means of raising the power-factor of a single-phase motor to values closely approximating 100 per cent., and having an operating value above 95 per cent.

This compensating field may be either conductively or inductively produced, depending upon whether the winding is traversed by the main motor current, or by the current produced in its own short-circuited winding by the alternating armature flux. So far as concerns operation from alternating-current supply, one form is about as efficient as another, but the conductive compensation is an aid when the alternating-current motor is called upon to operate as a direct-current motor.

The series-field winding of the single-phase compensated motor is connected in series with the armature, and the direction of rotation can be reversed by reversing the field-winding connections similar to direct-current operation. The series-field winding may be distributed in a number of slots in the field-magnet structure similar to the compensating-field winding or it may take the form of a concentrated winding, in which case it is similar to the winding of a direct-current series motor embracing inwardly projecting poles. The concentrated field winding is largely used in alternating current motors of the series type, while the distributed field winding is required for motors of the repulsion or similar types. As the series-compensated motor is universally used in this country, and the repulsion and similar types are limited to special cases demanding special characteristics of the motive power, the series type motor alone will be considered.

As the armature rotates in an alternating field, there is a short circuit developed when brushes touch two commutating segments at once. This

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short circuit is very large at starting, being reduced to a reasonable amount when running at full speed. To reduce the amount of this short-circuit current, and better the low-speed commutation, the alternating-current series compensated motor is sometimes provided with resistance leads connecting armature winding with commutator bars. Such leads are desirable with motors of the series compensated type, where full field strength is used in starting and there is no commutating-pole effect to neutralise the short-circuit voltage when moving

198. The repulsion motor as originally developed by Thomson and perfected is shown in Fig. 51. The field winding is very similar to the field winding of an induction motor. The armature is an ordinary series-wound armature short-circuited upon itself. The repulsion motor is very similar in its operating constants to the single-phase compensated motor but cannot be used for speeds much higher than 100 per cent. of synchronism, owing to the imperfect commutation at the higher speeds. It has the advantage of having its field circuit distinct from the armature circuit, hence, permitting

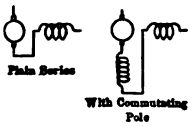


FIG. 49.

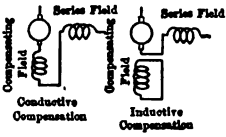


FIG. 50.

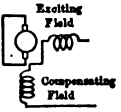


FIG. 51.

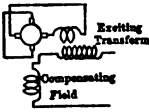


FIG. 52.

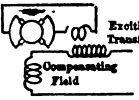


FIG. 53.

of a field winding of any potential best suited for control or operation. With this type of motor it is possible to operate 3,000 volts direct on the field winding if desired.

Best results appear to be obtainable from a combination of repulsion-motor connections for starting and operation at low speeds, changing to series-motor connections for speeds above synchronism. This is effected automatically by relays.

199. In the Latour motor, which is a modification of the Winter-Eichberg motor the armature winding is short-circuited in part only, rather than through diametrically opposite brushes, with the result that the armature I^2R loss is reduced. This type is limited in its field of application to special cases.

200. The three-phase induction motor has all the characteristics of a direct-current shunt-wound or constant-speed motor, and comprises a three-phase primary winding either star or delta connected, with a three-phase secondary winding either star or delta connected. The secondary terminates in collector rings across which non-inductive resistance is inserted during the accelerating period, after which the collector rings are short-circuited. The induction motor may be wound for the trolley potential if desired, as the potential of the secondary winding is entirely independent of that of the primary. The constant-speed characteristic of this type of motor is especially adapted for duty of a constant nature, such as haulage over a regular profile, either level or up a uniform gradient, in other words, where there is no combination of slow-speed grade haulage and high-speed level service.

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201. The single-phase induction motor has been used for railway purposes on experimental roads, but owing to the zero starting torque of this motor it is necessary to operate it in conjunction with an auxiliary starting device and throw the motive power into action by mechanical clutches or other means after full motor speed has been obtained. This type of motive power is very limited in its field of application.

202. The split-phase converter system comprises a method of obtaining polyphase current from a single-phase trolley, for the operation of polyphase motors. It consists of a phase converter which is essentially a polyphase induction motor the capacity of which is approximately 75 per cent. of the capacity of the motors it supplies. As the phase converter is operated from one phase only, it requires a starting motor to bring it up to near synchronous speed. In all applications of this principle, the single-phase current has been converted into two-phase current. In the Norfolk & Western locomotives, these two phases are changed to three-phase by a connection similar to the well-known Scott system. The advantage claimed for the three-phase is that the motor has a better performance and is also better for pole changing while it entails no more regulating switches and has fewer leads.

BRAKING

203. Retarding factors. In order to bring a moving train to a stop, it is evident that some external force opposed to the motion of the train must be applied. The ideal force would be applied at the centre of gravity of the car (producing no tendency for the car to rotate) and would be sufficient to stop the train in case of emergency in the shortest possible time, without undue shock to passengers or equipment. With the exception of a few instances, such as short cable roads up a mountain side, the only available force which may be utilized in stopping a train is the friction which exists between the wheels and the rails. This force, besides being applied at the lower rim of the wheel and consequently not at the centre of gravity of the car, is also a variable quantity of uncertain magnitude, and therefore not an ideal retarding force. For instance the adhesion between a dry rail and wheel may be equal to about 30 per cent. of the pressure between wheel and rail, whereas with a wet rail it may be only half that amount. The addition of sand to a slippery rail will increase the adhesion from 15 per cent. to about 25 per cent. of the weight on the rails, and this amount can usually be relied upon in making emergency stops. This force of 25 per cent. of the weight on the rails applied to a car will produce a retardation equal to one-quarter the acceleration due to gravity, or 8.04 ft. per sec. per sec., or nearly 5.5 miles per hr. per sec. If it were possible to apply this force instantly and uniformly throughout the stops, a stop from an initial speed of 60 miles per hr. could be made in about 11 sec., or in a distance of 480 ft. This force, however, is only available when the wheels are rolling on the rails, for as soon as slipping occurs the adhesion rapidly decreases. Therefore the force which opposes the revolution of the wheels, namely the brake-shoe friction, must never exceed that which is keeping the wheels turning, namely the adhesion between the wheels and rails. This opposing force is obtained in several different ways, the most familiar being by applying brake-shoes to the rim of the wheel with considerable force by means of hand or power brakes. Another method which is applicable in electric traction, is known as electric braking, as distinguished from mechanical braking, and consists in opposing the revolution of the wheels with the counter-torque of the motors or by the friction of electrically operated brake discs.

204. Tests to determine friction coefficients. About the first systematic tests to determine the value of the coefficient of friction between brake shoes and wheel, and between wheel and rail were conducted by Sir Douglass Galton and Mr. George Westinghouse in 1878 and 1879 on the London, Brighton & South Coast Railway, England. A report of these tests appears in the proceedings of the Institute of Mechanical Engineers of London, for April, 1879. The table in Par. **205** gives the results of these tests

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205. Coefficient of friction at various speeds. Cast-iron brake blocks on steel tires

Number of experiments from which the mean is taken	Speed		Coefficients of friction		
	Miles per hr.	Feet per sec.	Extreme maximum	Observed minimum	Mean
12	60	88	0.123	0.058	0.074
67	55	81	0.136	0.060	0.111
55	50	73	0.153	0.050	0.116
77	45	66	0.179	0.080	0.127
70	40	59	0.194	0.088	0.140
80	35	51	0.197	0.087	0.142
94	30	44	0.196	0.098	0.164
70	25	36½	0.205	0.108	0.166
69	20	29	0.240	0.133	0.192
78	15	22	0.280	0.131	0.223
54	10	14½	0.281	0.161	0.242
28	7½	11	0.325	0.123	0.244
20	Under 5	Under 7	0.340	0.156	0.273
.....	Just moving	Just moving	.....	.....	0.330
leeming Jenkin (steel on steel) 0.0002 to 0.0086.			0.337	0.365	0.351

ennie. Static Friction under
Pressure of 180 lb. per sq. in..... 300
Pressure of 336 lb. per sq. in..... 347

206. Variation of friction coefficient with speed. From the values ven in Par. **196,** Mr. R. A. Parke has developed the following **formulas.**

om the mean values $$f = \frac{0.326}{1+0.03532\ S} \qquad (19)$$

m the maximum values $$f = \frac{0.382}{1+0.2933\ S} \qquad (20)$$

here f = coefficient of friction, and S = speed in miles per hr. The latter rmula gives values corresponding more nearly to recent experiments.

207. Coefficient of friction as affected by time*

Miles per hr.	Commencement of experiment†	After 5 sec.	After 10 sec.	After 15 sec.	After 20 sec.
20	0.182	0.152	0.133	0.116	0.099
27	0.171	0.130	0.119	0.081	0.072
37	0.152	0.096	0.083	0.069	.....
47	0.132	0.080	0.070	.....	.....
60	0.072	0.063	0.058	.....	.....

208. Decrease of the coefficient of friction with length of brake plication is represented by Mr. R. A. Parke's formula, which is as llows:

$$f = \frac{1+0.000472\ l}{1+0.00239\ l} f^1 \qquad (21)$$

herein f is the coefficient of friction at beginning of application: f' the efficient of friction after brake application of T sec.

* Sir Douglas Galton has also published the following values of the coicient of dynamic friction as affected by time of brake application.

† The figures in this column are somewhat different from those that have st been given in the altered table, because they resulted from the average fewer experiments; but the effect of time in reducing the coefficient of ction may be accepted as correct.

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209. General laws affecting friction coefficient. The absence of more extended observations and the complex nature of fluctuations of the coefficient of friction make it impossible to formulate a practical mathematical equation which will determine the rate of retardation under varying conditions. However, the results of the tests shown in the tables above indicate a law of variations which may be briefly stated as follows, regardless of the materials used.

(a) The coefficient of friction increases with the decrease in speed;

(b) Decreases with the increased distance through which brakes are applied, and

(c) Decreases with the increase of pressure.

210. To obtain a uniform braking effort throughout the stop, the brake-shoe pressure must be varied to compensate for the fluctuations in the coefficient of friction, that is, the brake-shoe pressure must be decreased as the diminution in speed increases the coefficient of friction, and increased as the distance of brake application decreases the coefficient of friction, and further increased to compensate for the decrease of the latter with increased pressure.

For certain speeds the increase in coefficient of friction with decrease in speed is practically neutralized by a decrease due to increased distance of frictional contact. For lower speeds, however, the increase from the former cause is more rapid than the decrease from the latter, necessitating an almost abrupt decrease in brake-shoe pressure near the end of a stop, in order to avoid slipping the wheels on the rails and discomfort to passengers.

211. Efficient emergency braking. For the same pressure, the coefficient of brake-shoe friction at 60 miles per hr. is only about half that at 20 miles per hr. It is therefore evident that an emergency stop for high speed is less efficient than for a low speed, since an emergency application implies that the maximum pressure which will not slip the wheels near the end of the stop, is instantly applied at the very outset. A considerably shorter stop may be made if the pressure applied during the earlier period of the stop is greatly in excess of that which will slip the wheels at low speed, but in the absence of the motorman's skill, some means must be provided to decrease the pressure near the end of the stop, in order that the limits of maximum friction will not be exceeded, and the efficiency of the stop thereby decreased. This provision, however, requires additional apparatus, which on general principles is objectionable unless the showing is so favorable as to warrant further complications.

212. Application of the retarding force. Thus far, attention has been devoted to outlining methods for overcoming the obstacles presented by the complex nature of the fluctuations of the coefficient of brake-shoe friction which prevent the utilization of the theoretically possible retarding force. The nature of the application of these forces imposes difficulties which prevent the full utilization of the weight on the trucks and wheels, thereby directly affecting the braking force.

At the present time it is customary to equip double-truck cars with either two motors or four motors, depending upon the nature of the service. In the former case both motors are usually placed on one truck thus permitting the use of a lighter truck for a trailer. The pressure which may be safely applied to the wheels of the motor truck without causing the wheels to slide cannot be applied to the wheels of the trailer truck. Hence the brake rigging must be so proportioned that the greatest portion of the braking is done upon the wheels of the motor truck. Considering, however, the case where the normal distribution of weight is equal for all wheels, it is found that, during braking, a greater pressure may be applied to the wheels of the forward truck without causing them to slide than may be applied to the wheels of the rear truck. The explanation is somewhat simplified when considering single car operation, since draw-bar forces may be eliminated.

213. Vertical thrust on forward truck. The resultant of all the parallel forces, which act on the elementary masses of the car tending to keep it in motion, is equal to the sum of all these forces acting through the center of gravity of the car and in the direction of motion. Directly opposed to the motion of the car is the wind pressure, which is exerted normal to the elementary surfaces, the resultant passing approximately through the cen

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of gravity of the car. Wind pressure, however, is sufficient to cause only a slight retardation compared to that obtained with the brakes, and its effect has been neglected in this consideration. The retarding force of the brakes acts at the surface of the rail and as all parts of the structure are retarded equally, the king pins must transmit the force required to produce the same retardation in the car body as is produced in the truck. The total retarding force less the amount required for retarding the wheels and trucks therefore

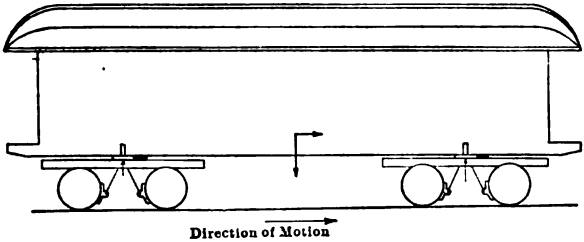


FIG. 54.—Braking-stress diagram.

acts at the points of support, which are somewhat lower than the centre of gravity of the car body. The moment of these forces about the centre of gravity of the car, is balanced by the moment produced by the increased pressure of the forward truck acting upward through the point of support; at the same time the weight on the rear truck is decreased.

214. The distribution of weight on the wheels of each truck is affected in the same manner, except that the retarding force transmitted through the king pins to the car body, also reacts to further increase the pressure on the front pair of wheels of each truck. Because either end of the car may at some time become the rear end, it is essential that the brake-shoe pressure be kept the same for all wheels which necessarily restricts the maximum pressure which can safely be employed to that which will not slip the wheels with the least weight. In the case of the eight-wheel passenger car, the effective wheel pressure which may be utilized in braking is only about 85 per cent. of that permissible with the total weight on the wheels.

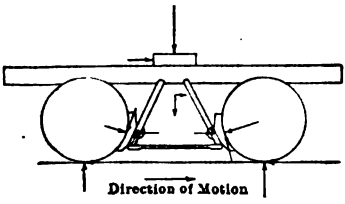


FIG. 55.—Stress diagram.

215. Location of brake-shoes affecting recoil at instant of stopping. On account of the stored energy in the revolving wheels, gears and armatures, which may amount to 5 or 10 per cent. of the total stored energy of the car, a consideration of the effect of these forces upon the truck through the brake hangers is essential. With outside-hung brake-shoes the pressure due to the friction between brake-shoes and wheel. is downward for the leading wheels, thereby causing compression of the forward springs of the truck. For the trailing wheel the pressure is upward, thereby relaxing the rear springs of the truck. The recoil of the forward springs results in the backward motion of the car body so disagreeable to passengers at the instant of stopping. With inside-hung brake-shoes, the brake-shoe friction force acts upward through the hanger links of the forward portion of the truck and downward through the hanger links of the rear portion of the truck, thus tending to neutralise instead of aggravate the effect of the rotating influence of the car body. The problem of proportioning the length of brake-shoe hangers and the proper inclination of the same to the tangent at the point of contact

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of the centre of the shoe, in order to compensate exactly for the rotating influence of the car body, is too involved for presentation here. For this reason reference is made to Mr. R. A. Parke's excellent paper in the Proceedings of the American Institute of Electrical Engineers, Vol. XXII, Dec., 1902

216. A common form of hand brake consists of a vertical shaft at each end of the car fitted at the top with a ratchet handle or crank, or geared to a hand wheel. By means of this mechanism, the motorman can wind up chain, one end of which is fastened to the lower end of the vertical shaft and the other end to a rod which connects with a system of brake levers. By means of a pawl (or dog) which engages in a ratchet wheel on the vertical shaft near the floor of the car, the motorman is enabled to maintain a pressure on the brake-shoe while he gains a more favorable purchase for applying more pressure, or until such times as he desires to release the brakes. The

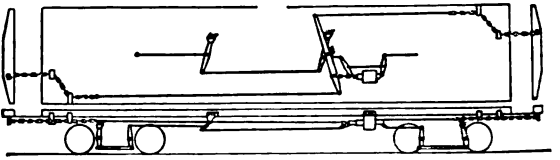


FIG. 56.—Diagram of brake rigging.

brake has been found capable of supplying sufficient braking power for the safe control of light cars running at moderate speed, but for heavy cars at high speeds the physical effort and time required to properly apply the brake render it necessary to provide other means of supplying the proper force in a minimum length of time. Hand brakes, nevertheless, are always provided as an additional safeguard, even though the cars may be equipped with power brakes, as it is always customary to set up the hand brakes on all cars when they are left standing.

217. Air-brakes (Par. **218** to **238**) in some form, have been universally adopted on all steam roads for braking both passenger and freight trains, and the results have been attended with such success that modifications and improvements of the old steam-railroad air-brake system have been developed and adopted by a vast majority of electric lines operating heavy high-speed interurban cars, either singly or in trains. On account of the varying character of the service on different electric roads, it has been found necessary to develop several systems, or modifications of the same system which will be best adapted for the service in hand.

The most familiar types at present are known as the following: *the straight air-brake system* (Par. **218**), recommended for single-car operation only; the *emergency straight-air system* (Par. **224**), suitable for two-car operation, particularly when one is operated single most of the time and with a trailer added during rush hours; *the automatic air-brake* (Par. **227**), suitable for electric trains of three cars or more; *the combined straight and automatic air-brake* (Par. **236**), designed for locomotive operation, no matter whether steam or electric; *the electropneumatic air-brake* (Par. **237**), at present in an experimental state, but particularly adapted to train operation, inasmuch as the time element in the application and release of the brakes on the rear end of a long train is practically eliminated.

218. The straight air-brake system described in detail in Par. **219** to **223**, consists essentially of a source of compressed air (either a tank filled at intervals from a compressor at charging stations, or an air compressor, motor or axle driven, located upon the car); a reservoir which receives the air from the charging tanks or from the compressor and in which the pressure is maintained practically constant by means of a reducing valve, or by a governor which automatically controls the operation of the compressor; a brake cylinder, the piston of which is connected to a system of brake levers in such a manner that when the piston is forced outward by air pressure the brakes are applied; an operating valve mounted in each vestibule by means of which the compressed air is either admitted or released from the brake cylinders; a pipe system connecting the above parts, including cut-out valves, extra hose

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and angle fittings between cars. In order to prevent any possibility of accumulating an excessive pressure, a safety valve designed to open at 100 lb. per sq. in. is placed in the air-supply system. A set of pressure gages is usually supplied with each complete equipment in order that the motorman may observe the pressure in the reservoir and remedy any defects in the governing apparatus.

219. To operate the motorman's valve (Par. 218), the handle is inserted when the valve is in lap position, where the slot in the body of the valve is enlarged for this purpose (in order to prevent its removal in any other position). In this position the valve is set so that air can neither pass into nor out of the brake cylinder. Moving the handle to the left places the valve in "full release," that is, connects the brake cylinder to the atmosphere and allows the air which holds the brakes applied, to escape, and the spring which is opposed to the air pressure, restores the piston and releases the brakes. After the brakes have been released the valve is returned to lap position, which is the normal running position. To partially release the brakes, which is necessary in braking in order to prevent shocks as the car stops, the handle is moved to the right and quickly returned to lap. This reduces the pressure on the brake-shoes, but does not entirely release them.

220. To apply the brakes for a service stop (Par. 218), the handle is moved to the right a little past the lap position, then back to the lap. This connects the reservoir with the brake cylinder through a small opening in the

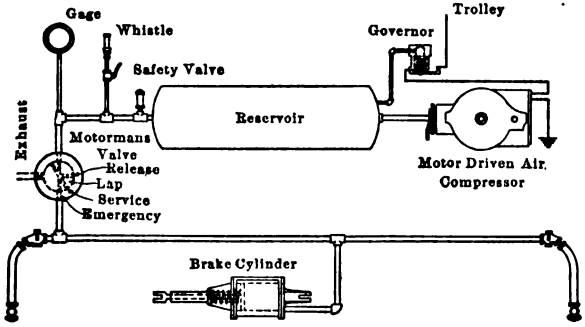


FIG. 57.—General Electric straight-air brake system.

valve, then holds the pressure constant until it is necessary to release or apply more pressure. Moving the handle further to the right connects the reservoir to the brake cylinder through a large opening, thus causing the cylinder to fill rapidly and instantly apply the brakes with maximum pressure. Sand is usually applied to the tracks as soon as the handle is turned to the emergency position in order to avoid skidding the wheels.

221. In descending grades (Par. 218), a light application of the brakes should be made and the handle returned to lap. A sufficient length of time should be allowed for car to feel the effect of the brakes before applying more pressure. If speed is higher than desired a second light application should be made and operation repeated as often as necessary until the desired speed is obtained, or until the car has left the grade.

222. Use with trailer (Par. 218). The straight-air system of air-brakes although only recommended for single-car operation, may be used when, operating with a trailer. The equipment for trail cars consists of a brake cylinder and system of levers similar to the ones on the motor car, and a length of pipe running the entire length of the car and provided with hose couplings and cut-out cocks for connections to the forward and rear cars. In connecting up train cars, all the hose couplings must be thoroughly united

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to insure that air will apply throughout the entire train. All the cut-out cocks must be open except those on the rear of the last car, and the front of the first car.

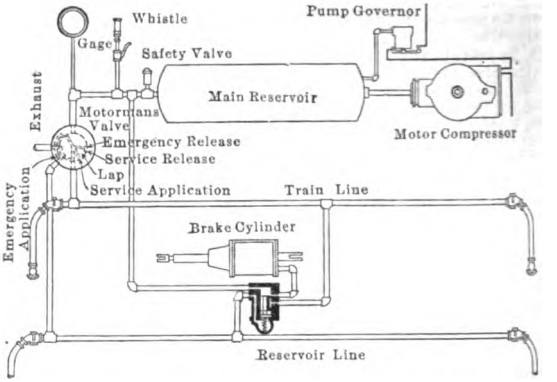


FIG. 58.—General Electric emergency straight-air brake system.

223. Field of application (Par. 218). So far as single-car operation is concerned, the straight air-brake system is very satisfactory, as the desired flexibility in the matter of graduations of applications and release of the brakes with due regard to the passengers standing can readily be secured, and this apparatus is usually so simple in construction that the motorman may become familiar with its operation to such an extent that accurate stops may be secured with a minimum amount of instruction. In trains of considerable length, however, the response of the brakes on the rear cars is too slow, since all the air must pass from the main reservoir on the front car through the opening in the motorman's valve to the brake cylinders of each car. As the addition of each car adds to the volume of the brake system, the main reservoir on the first car must be considerably increased. The reservoir capacity must be so proportioned that the pressure will not be reduced to such an extent that the brake application will be insufficient and result in overrunning the desired stopping place. These latter objections would not necessarily prevent the use of this type of air-brakes on short trains of two or three cars, were it not for the objection that a broken hose connection or leaky train pipe renders the brakes on the whole train inoperative.

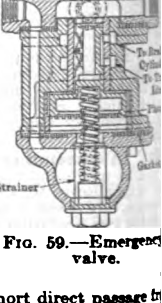


FIG. 59.—Emergency valve.

224. The emergency straight air-brake, described in detail in Par. **225** and **226**, differs from the straight air-brake in the details of the motorman's valve and in the addition of an emergency valve and reservoir line which connects the motorman's valve with the emergency valves (Figs. 58 and 59). In the case of a trail car, an auxiliary reservoir (Par. **226**) is also added, as shown in Fig. 60.

In the ordinary operation of single cars or short trains, the emergency valve is seldom brought into play. It is necessary, however, to provide a short direct passage from the reservoir to the brake cylinder in order to ensure the quickest possible action in time of emergency and to provide some means of automatically braking the rear cars should a break occur in the train line. At other

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times when it is desired to make a service application or release, the air is admitted or exhausted through the motorman's valve the same as in the straight air-brake.

225. Emergency application (Par. 224). With the motorman's valve in the emergency position, it allows air to escape from the reservoir line and causes the reservoir pressure, which is above that in the emergency valve, to compress the spring which holds the valve in its normal position, thus opening a port in the valve casing which communicates with the brake cylinder for the direct passage of the reservoir air. The line from the reservoir supplying the air for this process should not be confused with the reservoir line. During an emergency application, all communication with the train and reservoir lines is cut off. To release the brakes, therefore, it is necessary first to return the emergency valve to its normal position by recharging

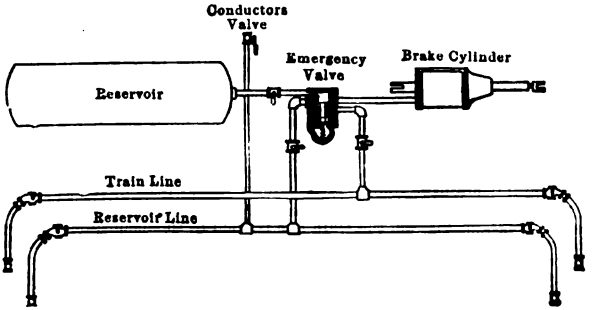


FIG. 60.—General Electric emergency straight-air brake for trail cars.

the reservoir line to the reservoir pressure. This equalising of pressures allows the spring under the valve to return it to its original position, and the brakes can be released in the same manner as after a service application by exhausting the air from the train line. The recharging of the reservoir line is accomplished by moving the motorman's valve to emergency-release position at the extreme left of the slot in the body of the valve. With the motorman's valve in this position, a connection is opened between the main reservoir and the reservoir line and also a connection between the train line and atmosphere. With the emergency valve in normal position there is a direct passage to the train line and brake cylinder, and the service applications and release are made by increasing or decreasing the pressure in the train pipe.

226. Auxiliary reservoir with trailer (Par. 224). In the case of a trail car, the auxiliary reservoir is charged during emergency release by the air pressure equalising on both sides of the slide valve through charging grooves in the valve casing. At other times it is charged from the main reservoir through the charging grooves in the emergency valve on the motor car.

In case of accident to the reservoir line the air can be exhausted from the auxiliary reservoir and the train operated on straight air without interrupting the service. An accident to the train line has no effect upon the action of the emergency valve which still can be employed as ordinarily by throwing the motorman's valve to the emergency position. As the straight-air-brake principle predominates in this system, it is subject to the same objection which prevents the use of the straight air-brake on longer trains, namely the time limit. For this reason, the automatic air-brake is used on trains of three or more cars.

227. The automatic air-brake, described in detail Par. 228 to 235, differs from the straight air-brake in that the former requires a decrease in the train-pipe pressure to apply the brakes, and an increase in pressure to

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release them, whereas in the latter, air is admitted to the train pipe to apply the brakes and exhausted to release them.

223. The apparatus required (Par. **227**) for this system in addition to that already mentioned for the straight air-brakes is as follows: a set of duplex pressure gages, which indicate simultaneously the pressure in the main reservoir and in the train pipe; an auxiliary reservoir, for storing the air used by each car in braking; a triple valve, the function of which is to admit air from the auxiliary reservoir into the brake cylinder and to release it therefrom (in release position, the auxiliary reservoir is recharged), and an air-whistle reservoir, with suitable check valve for supplying air to the air whistle.

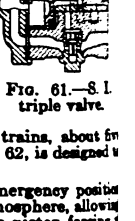


FIG. 61.—S. L. triple valve.

This system is capable of a great many refinements which may be added or omitted as requirements of a particular service may prescribe. The main points of difference between particular automatic air-brake equipments will generally be found in the details of the triple valves, and the addition of pressure maintaining and reducing valves. These features are essential in certain classes of grade work in order to prevent brakes "leaking off." These particulars have been intentionally omitted from this consideration in order to avoid undue complexity. Two forms of triple valves, however, need to be considered here inasmuch as the plain triple valve, Fig. 61, is only used on comparatively short trains, about five cars in length, whereas the quick-action triple valve, Fig. 62, is designed to be used on much longer trains.

229. Emergency application (Par. **227**). For the emergency position shown in diagram, Fig. 62, the train line is open to the atmosphere, allowing auxiliary reservoir pressure on the right of the slide-valve piston forcing it to the left against the graduating spring, compressing it and uncovering the brake cylinder port. Air is thus permitted to flow from the auxiliary reservoir directly into the brake cylinder; at the same time the ports leading to the atmosphere and to the train pipe are closed.

230. To release the brakes (Par. **227**), the main reservoir air is admitted through the train to the chamber at the left of the slide-valve piston, forcing it to the right, and connecting the brake-cylinder port to the exhaust pipe. At the same time, air at the main reservoir pressure raises the check valve and recharges the auxiliary reservoir to main reservoir pressure.

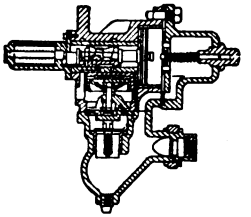


FIG. 62.—K triple valve.

A **graduated release** of the brakes may be obtained with this type of valve, by piping the exhaust from the triple valve to the motorman's valve where a movement of the valve handle will release the air the same as in the straight air-brake.

231. Necessary train-line reduction (Par. **227**). A service application requires only a slight reduction in train-line pressure (from 5 to 7 lb.) which is sufficient to permit the slide-valve piston to slightly compress the graduating spring and partially open the brake-cylinder port. When the auxiliary reservoir pressure has been reduced to about the same value as the train-line pressure, the graduating spring will return the slide valve to lap position, closing all the ports before the brakes are fully applied. The auxiliary reservoir and brake cylinder are usually so proportioned that the brakes are fully applied when the brake piston displacement is sufficient to reduce the auxiliary reservoir pressure about 15 lb. Therefore, a train pipe reduction greater than 15 lb. fully applies the brakes and is wasteful of air because the train pipe and the auxiliary reservoir must be fully charged after each application.

232. The quick-action triple valve (Par. **227**), shown in Fig. 62, is designed to be used on freight trains of considerable length, its function is to apply and release the brakes on the rear cars so quickly that the running in and out of the slack is avoided. Fig. 64 is a diagrammatical section of the

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triple valve shown in Fig. 62. In the full release position shown, air is allowed to pass from the brake cylinder through ports in the slide valve, the same as in the plain triple valve. The auxiliary reservoir is charged through grooves around the slide-valve piston, and also through the raised check valve and the uncovered port in the slide valve. The operation of the automatic air brake (Par. **227**) in conjunction with this valve is described in Par. **232** to **235**.

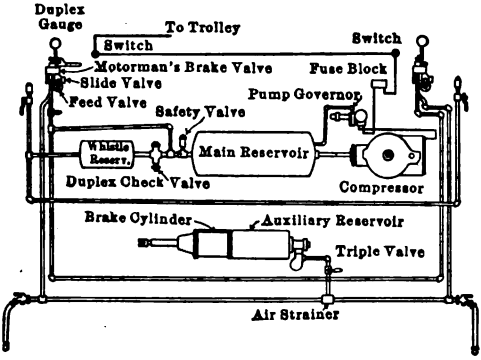


FIG. 63.—Westinghouse automatic air-brake.

233. Release with quick-action triple valve (Par. **227** and **232**). In release position, the decrease in train line pressure allows the valve piston to move to the left, closing the charging grooves and feed port, *J*, and exhaust port, *P*. Just before valve piston strikes the graduating stem, a cavity in the grading valve on top of the slide valve connects ports which allow communication from the brake cylinder to the emergency chamber and train pipe. The piston in the emergency chamber is only loosely fitted, so that the air which is admitted from the train pipe to the unseated check valve passes into the brake cylinder before communication is established between the auxiliary reservoir and the brake cylinder. Owing to the friction in the train pipe, a reduction of air pressure at the front end of the train is not felt at the rear end until some time later. Thus the venting of the train pipe at each car results in hastening the reduction for each car following; at the same time requiring a less reduction at the engineer's valve to apply the brakes with a given pressure, since the auxiliary reservoir is not required to supply all the air to the brake cylinder.

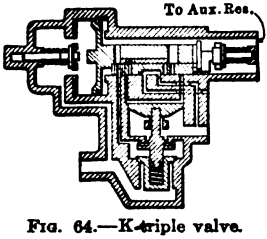


FIG. 64.—K-triple valve.

When the brake-cylinder pressure is reduced below that in the train line, the slide-valve piston moves to the right with the graduating valve and closes all ports leading to the brake cylinder. The tendency for the brake-pipe and auxiliary-reservoir pressures to equalise through the connections to the brake cylinder is prevented by the proportioning of the respective ports, so that the auxiliary-reservoir pressure decreases faster than the brake-pipe pressures, and insures the travel of the piston to the right.

234. In retarded release with quick-action triple valve (Par. **227** and **232**) the train line is quickly re-charged, forcing the valve piston to the extreme right. Thus is prevented the re-charging of the auxiliary reservoir

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through the charging grooves before opening a small port in the slide valve would permit the train line pressure to raise the check valve and slowly re-charge the auxiliary reservoir. The function of the charging device (shown on the outside of the valve in Fig. 62) is to prevent the inertia of the slide valve from forcing it to the extreme right of its travel when the valve piston is brought up against its stop. The restricted area at the left end of the exhaust cavity of the slide valve partly closes the exhaust port, and allows the brake-cylinder air to flow slowly into the atmosphere. On account of the friction in the train pipe, it is impossible to re-charge the train line at the rear of the train faster than the air will flow through the charging grooves of the triple valves. As a result, only the triple valves of the foremost cars move to retarded release, the others remaining in full release, which releases the brakes on the rear cars quickly.

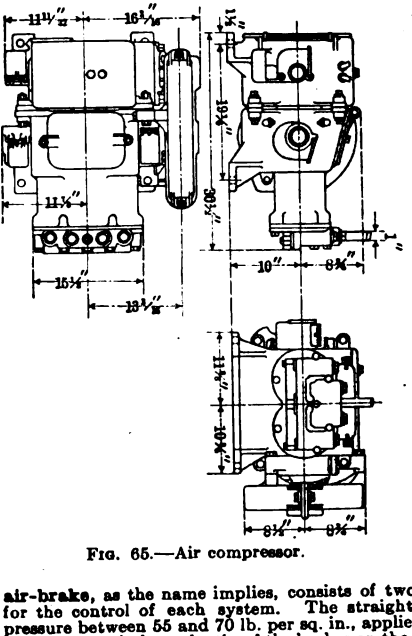


FIG. 65.—Air compressor.

238. Emergency application with quick-action triple valve (Par. 218 and 223). The sudden reduction of train pipe pressure in the emergency position of the engineer's valve, moves the slide valve piston to the left, compressing the graduating spring and opening the port directly to the brake cylinder, and also opening another port to the emergency chamber which unseats the emergency valve. At the same time the train-line pressure opens the check valve and air flows from the train line directly into the brake cylinder, applying the brakes with maximum pressure. The quick venting of the train line insures the rapid serial action of the brakes on the rear cars.

236. The combined straight and automatic air-brake, as the name implies, consists of two sets of motorman's valves for the control of each system. The straight air-brake, operating with pressure between 55 and 70 lb. per sq. in., applies and releases the brakes on the front car independently of the brakes on the other cars. The automatic brakes operate with air pressure from 100 to 110 lb. per sq. in., and apply the brakes on the remainder of the train independently of the brakes on the front car. The chief advantage of such an arrangement is the possibility of holding the brakes on the locomotive applied while the train brakes are released for the purpose of re-charging the auxiliary reservoirs.

237. The electropneumatic system is practically the same as the present automatic system, except that the valves are operated by solenoids in much the same way as the contactors in the multiple-unit train control. At the present time air control is retained as a safeguard in case of failure of the electric control. With electric traction, the possibilities of this system seem to be unlimited and automatic retardation as well as acceleration is quite feasible.

238. The air reservoirs should have a capacity sufficient to supply air for three or four applications without reducing the pressure more than from 5 to 15 lb. Otherwise every ordinary application of the brake will throw

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the compressor into action, thus keeping the latter in a constant state of starting and stopping, and causing unnecessary wear to both compressor and governor. The Westinghouse Traction Brake Company recommended the following sizes of reservoirs:

With 8-in. brake cylinders use 16 in. × 48 in. reservoirs.
With 10-in. brake cylinders use 16 in. × 60 in. reservoirs.
With 12-in. brake cylinders use 16 in. × 72 in. reservoirs.

The lengths given above are over all.

These reservoirs are fitted with drain cocks, and should be drained frequently in order to prevent any water, oil, or dirt, brought in by the compressed air, from being carried further into the brake system. If allowed to stand for several days, the reservoir will fill with water, thereby reducing its capacity, and will also allow moisture to pass into the piping system and collect in pockets, where it will be likely to freeze in cold weather.

239. Track brakes have been developed for operation in connection with either power or hand brakes, the distinctive feature being the utilization of the power generated by the motors, when properly connected, to energize a powerful electromagnet, thereby drawing a suitable track shoe to the rail with considerable force. The friction between the track shoe and rail is transmitted to the brake shoes on the wheels through a system of brake levers, thereby adding to the braking effort of the brake shoes on the wheels an amount equal to the drag of the track shoes on the rails and the counter torque of the motors acting as generators. It is possible, because of the automatic regulation of the magnetic attraction between the track shoe and rail, to utilize as great or possibly greater brake-shoe pressure than is customary with either hand or air brakes without skidding the wheels, but in practice this is seldom required and considerably less braking pressure is customary. The friction, between the track shoe and rail, necessary to produce the requisite brake-shoe pressure will depend upon the design of the link motion and the speed of the train. However, this is usually greater than the braking effort exerted by the wheel brakes, and where the speed is low, advantage can be taken of a high coefficient of friction which is impossible where the wheels are apt to skid, as in the case of power brakes. It is thus evident that the retardation possible with track brakes is at least twice as great as with power brakes, rendering the former particularly well adapted as emergency brakes for heavy grades, which are characteristic of scenic railways, etc.

It should be noted, however, that since this brake depends upon the electromotive force generated by the motors when running as generators, it cannot be depended upon to hold a train on a grade or bring it to a stop unless a connection is made with the trolley for this purpose. There are various objections to resorting to this means of energizing the brake solenoid, except in an emergency, consequently the electric track brake is limited in its applications to roads where it is necessary to provide an additional safeguard at the expense of considerable complications to the ordinary form of brakes.

TRUCKS AND CAR BODIES

240. Classification of trucks. The development of the self-propelled car has led to some modifications in standard truck design. The several types of trucks all fall in two general groups—namely, the single-truck (Par. **241**), and the double or bogie truck (Par. **242**).

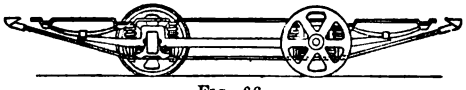


FIG. 66.

241. The single-truck car is intended for city-street service, and where the maximum speed does not exceed 25 miles per hr. The two axles of the single-truck are rigidly aligned by side frames, so that of necessity the rigid wheel base must be short in order to negotiate sharp curves, thus limiting the length of car used, because too much overhang is productive of much rocking and unsafe riding, and is objectionable also when rounding sharp curves in city streets. In order to provide easy riding, the car superstructure is sup-

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ported upon **elliptic and coil springs** designed to take up the shock resulting from riding over uneven track. Single-truck cars are limited to a maximum length of about 30 ft. over all and a maximum weight including car body and trucks, but exclusive of electrical equipment of approximately 15,000 lb.

242. The double-truck car is equipped with two distinct trucks joined together through the medium of the car-body framing. The swivel or **bogie truck** consists essentially of two or more axles centred in common side frames which are joined by a cross piece or bolster carrying a central plate and also side-bearing plates upon which the car body rests.

The bogie truck may comprise two or more axles mounted in a single structure, the prevalent type, however, is composed of two axles for cars weighing up to 50 tons total weight. For very high-speed service or for heavy cars, three-axle trucks are to be recommended.

243. Classification of bogie trucks. The standard four-wheel bogie truck is built along different lines depending upon the service which it is to perform. As the weight of the car body is carried upon the cross piece or **bolster** connecting the side frames, it is evident that the construction of this bolster and its support offers a means of cushioning the effect of shocks given the car wheels when riding over uneven track. There are three general types of bogie trucks, namely: the rigid-bolster type (Par. **244**), the floating-bolster type (Par. **245**); and the swinging-bolster type (Par. **246**).

244. The rigid-bolster type (Par. **243**) is suitable for locomotive work only, as the cushioning effect of the car body by means of springs is not carried to sufficient length for easy riding qualities. The bolster is solidly fastened to the side frames and forms an integral part therewith. The sprung suspended car superstructure is sustained by means of box springs

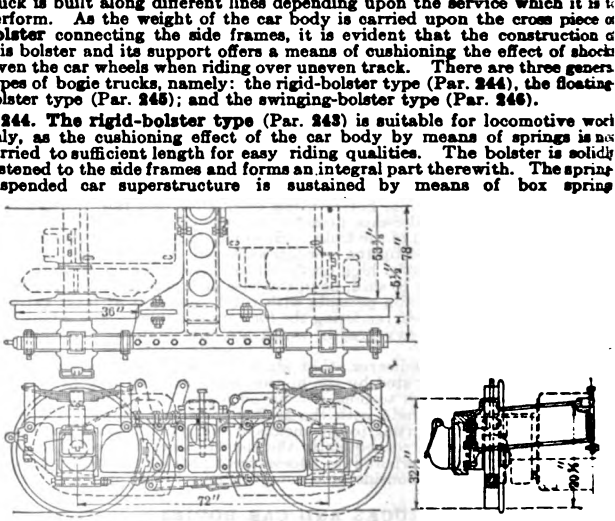


FIG. 67.—Motor, locomotive-frame, rigid bolster.

placed between the side frames and the journal boxes. These springs may be of semi-elliptic (Fig. 67) or spiral type (Fig. 70). This type of construction offers no compensation for the swaying of the superstructure, and is therefore not adapted for high-speed or passenger service.

245. The floating-bolster construction (Par. **243**), comprises in part a bolster mounted upon elliptic springs which rest upon the side frames. The bolster thus has an independent vertical movement, and travels in ways in the side frame. This type of construction is best adapted to locomotive trucks designed for slow-speed service, as the superstructure is not sufficiently cushioned to provide easy riding for high-speed passenger service.

246. The swinging-bolster construction (Par. **243**) comprises a movable bolster traveling in a guide or transom and mounted upon elliptic springs, a construction very similar to the floating-bolster type. In the former, however, the elliptic springs do not rest directly upon the side frames, but rest in a saddle hung from the transom or side-frame construction in such a manner that opportunity is provided for a transverse swing of the super-

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structure. This arrangement permits the superstructure to swing or roll when rounding curves, and offers a very easy riding truck for high speed passenger service. To increase the cushioning effect still further, the side frames are not directly mounted upon the journal boxes but have coil springs interposed, either placed directly over the journal boxes (Fig. 70) or between the side bar and the truck frames (Fig. 69) or a combination of both.

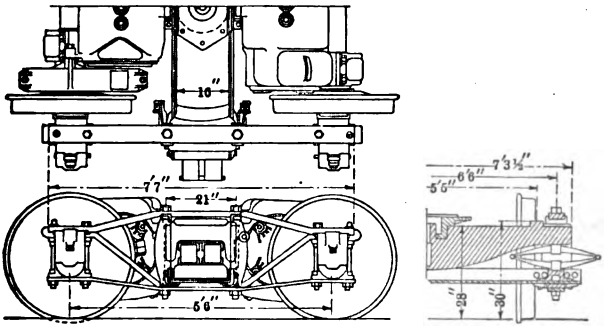


FIG. 68.—Arch-bar type, floating bolster.

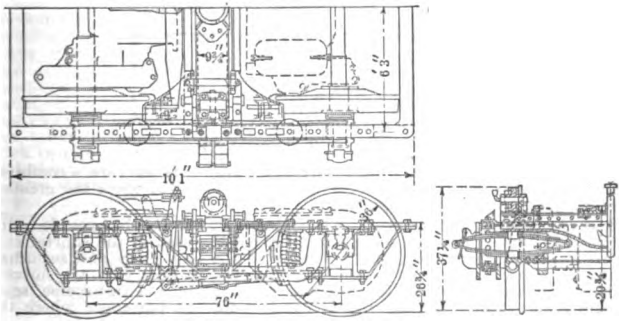


FIG. 69.—Bar frame, swinging bolster.

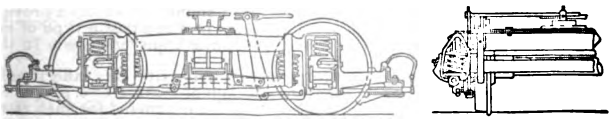


FIG. 70.—Swing bolster truck (Brill Co.).

The swinging-bolster truck is designed for high-speed passenger service, and is satisfactory for maximum speeds up to 70 or 80 miles an hour. For very high speeds it is preferable to provide a bogie truck construction consisting of three axles, the two outside axles carrying less weight than the centre axle, and preferably carrying no motors geared thereto.

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247. Construction of bolster and side frames. The truck bolster may be made of wood or metal, and both the centre plate and side-bearing plates which it carries, may be ball or roller bearings, in order to reduce the friction and permit the truck to respond readily to the demands of track curvature. The side frames may be built up of steel plates riveted together, or forged or cast in a single piece. The construction is rigid and provides for good alignment of the axles.

248. Maximum traction trucks are designed for city service at speeds not much exceeding 30 miles per hr., and are useful where it is desired to mount a single motor on a truck providing for four wheels, having a short wheel base, and carrying 70 per cent. of the total car weight upon the driving wheel, which is larger in diameter than the trailing wheel. Maximum traction trucks are not suitable for high-speed service.

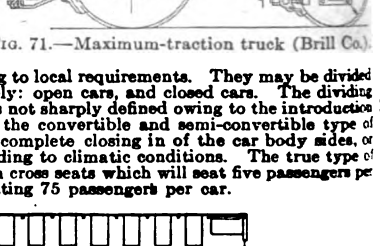


FIG. 71.—Maximum-traction truck (Brill Co.).

249. Classification of car bodies. Car bodies differ in construction according to local requirements. They may be divided into two general types, namely: open cars, and closed cars. The dividing line between these two types is not sharply defined owing to the introduction during the past few years of the convertible and semi-convertible type of car body, which permits the complete closing in of the car body sides, or partial removal thereof according to climatic conditions. The true type of open-car body is arranged with cross seats which will seat five passengers per seat and in the larger cars seating 75 passengers per car.

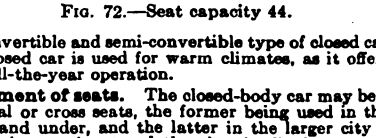


FIG. 72.—Seat capacity 44.

Besides the convertible and semi-convertible type of closed cars, a combination open and closed car is used for warm climates, as it offers the greatest advantages for all-the-year operation.

250. Arrangement of seats. The closed-body car may be provided with either longitudinal or cross seats, the former being used in the shorter cars of 30 ft. overall and under, and the latter in the larger city and suburban cars. In general it may be stated that longitudinal-seat cars are suitable only for short runs and medium rates of acceleration, and transverse seats should be used in order to provide comfort for the passenger where the accelerating rates are high or the run extended.

The prevalent type of transverse-seat car is indicated in Fig. 72, and usually contains short longitudinal end seats in addition. Owing to the possibility of crowding at the car entrance, it has been found advisable to provide more standing room at these points. This leads to a composite type of car having longer longitudinal end seats and providing transverse seats in the centre portion of the car only.

In some instances it is necessary to provide narrow city cars, and insufficient space is allowed for transverse seats capable of seating two people on the side. A modification of transverse-seat car is constructed for such cases having the longitudinal aisle and providing a two-passenger seat on one side and a one-passenger seat on the other.

251. Entrances and exits. In rapid-transit service, where large crowds must be handled with a minimum time allowed for stops, it is desirable to use doors at the sides so arranged that the crowd can circulate rapidly, with as little interference as possible between the boarding and the leaving passengers. In some cases this is accomplished by end doors for entrance and a

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centre door for exit, while in one type of side-door car there is a door opposite each seat, all doors being operated from one point by compressed air. These types of cars were originally installed for train operation on subway and elevated lines, where only station stops were made and where fares were collected before passengers boarded trains. It was some time afterwards that serious thought was given to the adoption of a similar principle in car body designs for operation on surface lines, that is, before steps were taken to separate the entrance from the exit or to collect fares as the passengers boarded the cars. The first cars brought out employing this principle, were known as **Pay-as-you-enter** cars and were similar in design to other cars then in use. The new features were closed vestibules with door control handles for the motorman and conductor and a fare box. Thus the front platform was converted into an exit which relieved the congestion around the rear platform when passengers desired to get on or off. This arrangement was a decided improvement over the older method of collecting fares after the passengers were seated and many lines charged over their old cars to make use of the pay-as-you-enter principle.

The next step was the design of a new type of car body with a front entrance and centre exit. In this type of car the centre exit is assumed to divide the car into two sections, a pre-payment section in the rear and a **pay-as-you-leave** section in front. The conductor is stationed just in front of the centre exit and collects the fares as the passengers pass him on their way to the pre-payment section or as they pass out. Such a car has the advantage of quick loading at transfer points and gives the conductor an opportunity to collect the fares and distribute the passengers in the car before reaching the next stop. There have been a number of other new features added in the design of these cars, notably an air-operated sliding door for the centre exit, low wheels and low step, vertical and horisontal grab rails instead of straps for standing passengers, dome shaped roof with exhaust ventilators instead of Monitor roof, flush platforms and other improvements in car body which do much to reduce the weight of the car and economize in space.

252. Safety or one-man cars. The development of safety features such as closed vestibules and mechanical control of the doors has made it possible to advance another step in the solution of the street railway transportation problem. This advance is on the theory that if a more frequent headway is maintained more passengers will ride and in the interval between cars fewer passengers will assemble who will have to be accommodated. With two-man cars the platform expense prohibits the operation of cars on such short headway and the seating capacity of the ordinary two-man cars is more than would be required for the passenger who would ordinarily be picked up on each trip, if such short headways were operated. The application of this theory required the development of special features in car-body designs so that one man could collect the fares as the passengers boarded the car, close the doors so that passengers could not get on or off while the car was in motion and also operate the car. The success of the venture is due largely to the details of the safety features which have been incorporated in the control which is so interlocked that one man can perform the duties of motorman and conductor. The door control and other safety features are worked out in conjunction with the air-brake equipment.

253. Extra compartments on suburban cars (Par. **254**). For suburban service it is desirable to provide a smoking compartment divisioned off from the main portion of the car and connected to it by a door. Such a car should preferably be run single ended with the smoking compartment in front. However, it is common practice to run such cars double ended, in which case all passengers may be compelled to pass through the smoking compartment in order to reach the main seating portion of the car.

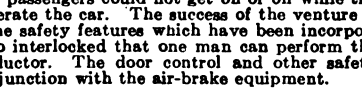


FIG. 73.—Single-ended car.

Owing to the necessity of taking care of baggage or express material on suburban lines, many such cars are supplied with a baggage compartment which is also used as a smoking compartment, and in addition a toilet should be provided where the run is of considerable length.

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254. Arrangement of interurban cars. Many cars are heated (Sec. 22), with hot water instead of electrically, and the more elaborate high-speed interurban cars operating over long distances provide a compartment for express matter, smoking compartment, main passenger compartment, toilet rooms, etc. The motorman's compartment is divisioned off from the baggage compartment and such cars are generally run single-ended, requiring the use of a loop or Y at the terminals, see Fig. 73.

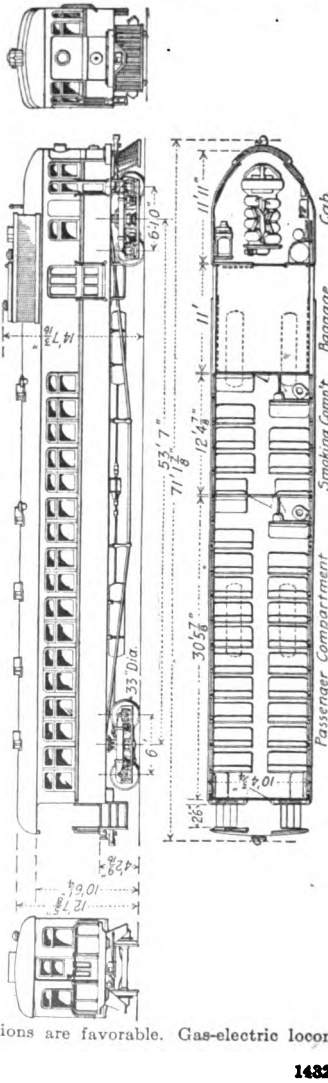


FIG. 74.—General Electric gas-electric car.

255. Double-deck cars. For certain classes of city service where the track capacity is limited and speeds are moderate, recourse may be had to a double-deck or top-seated car. Unless enclosed these cars are only suitable for climates having small temperature change and must be operated at low speed (20 miles per hr. or less) in order to prevent possibility of overturning. Access is had to the upper seating portion of the car by means of stairways.

SELF-PROPELLED CARS

256. Classification. Self-propelled cars are divided into three general types, as follows: storage battery (Par. 257); gasoline or oil motor (Par. 258); gas-electric (Par. 259).

257. The storage-battery car is suited to very special conditions, and has not yet been considered for general railway service owing to the limitations in weight, cost and restricted mileage of the battery. (See Section 20.)

258. The gas-motor car has come into limited use on interurban lines and on feeder lines of steam roads. Its greatest disadvantage lies in the mechanical transmission of power between motor and driving wheels.

259. The gas-electric car (Fig. 74) claims as its advantage the elimination of all mechanical troubles by substituting electric drive through generator and motors. Such cars are in service to a limited extent where operating conditions are favorable. Gas-electric locomotives are possible only when the

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service demand can be taken care of by the maximum output of the gas motor, not much exceeding 250 h.p. The possibilities of the gas-electric drive are not yet fully worked out or appreciated by operating men, and the use of such equipment is influenced largely by the possibility of using a cheap fuel. Cars are now in interurban service that consume approximately ½ gal. of gasoline per car-mile.

ELECTRIC LOCOMOTIVES

260. Classification. Electric locomotives may be divided into four general classes as follows: (a) miscellaneous interurban freight service; (b) yard-shifting and interchange freight; (c) main-line freight; (d) main-line passenger.

261. Locomotives for interurban lines are all of the same general type of construction and comprise a cab carried on two four-wheel trucks upon which are mounted single-geared motors in the usual manner. The locomotive is of construction similar to interurban cars, except as to super-

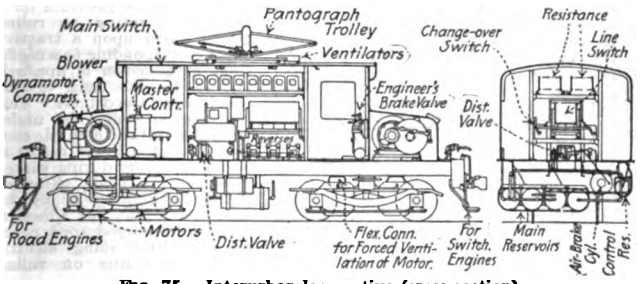


FIG. 75.—Interurban locomotive (cross-section).

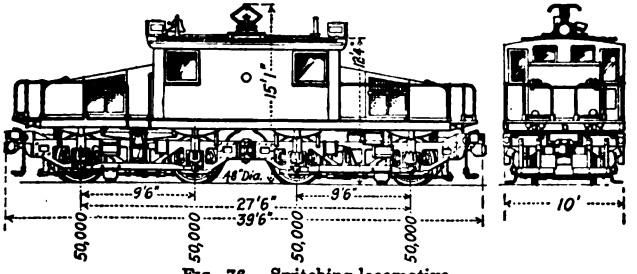


FIG. 76.—Switching locomotive.

structure and gearing of motors. The service performed by electric locomotives on suburban and interurban lines can generally be taken care of by a locomotive weighing from 30 to 60 tons, all weight being disposed on the drivers, and equipped with four geared motors of standard types. These motors have an aggregate capacity not greatly exceeding 1,000 h.p. at a 1-hr. rating. The trains hauled may reach 15 or 20 cars, totalling 500 to 800 tons as a maximum, while the average service comprises the movement of freight trains of considerably less number of cars. The duty of interurban locomotives is quite variable and is of such an intermittent character as seldom to require accurate predetermination of motor capacity.

262. Switching (yard) locomotives are of the same general type as those in use on interurban lines, except that the speed is much lower and the

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the total weight may reach 100 tons when such locomotives are used between large yards for the interchange of freight. The service is intermittent and the average speed is below 4 miles per hr. The average energy input is less than 80 kw. for a 60-ton locomotive. Slow-speed armatures and a maximum gear ratio are best suited for the service. Often two motors are connected permanently in series in order to limit the maximum speed and power demand to reasonable amounts. While yard locomotives will vary from 30 to 100 tons total weight, good examples of the heavier types are given in succeeding paragraphs.

263. Main-line freight locomotives present a great variation in design and motor equipment. Main-line service demands a locomotive equipment capable of withstanding a large sustained output, and hence calls for different motor characteristics than those which meet the requirements of city and interurban railway service. Steam-locomotive practice provides for a locomotive rating on ruling grade, based upon a tractive effort corresponding to a coefficient of adhesion of approximately 18 per cent. of the weight upon the drivers. This is exceeded somewhat under favorable rail and climatic conditions, but a lower rating is found necessary during winter months in cold climates. Hence assumption of 18 per cent. coefficient of adhesion may be considered good practice in determining electric locomotive rating on ruling grades.

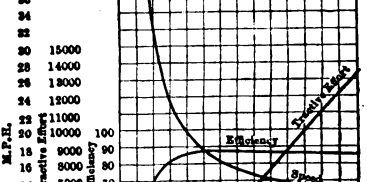


FIG. 77.—Motor characteristics Butte Anaconda & Pacific direct-current locomotive.

264. Example of calculation of permissible trailing load. An electric locomotive weighs 100 tons, all weight being disposed on drivers, what trailing load rating can it be given on 1 per cent. grade?

	Lb.
Tractive effort due to grade of 1 per cent. =	20
Tractive effort due to train resistance =	6
Total,	26
Locomotive tractive effort = 200,000 × 18 per cent. =	36,000

36,000/26 = 1,385 tons gross train weight

1,385 − 100 = 1,285 tons trailing

In Fig. 77 are presented the characteristic performance curves of the Butte, Anaconda and Pacific type of locomotive motor. This operates with direct-current supply at 1,200 volts (two in series for 2,400 volts).

265. The maximum tractive effort of a main-line freight locomotive should correspond to a coefficient of adhesion of 30 per cent., as this value is reached under good rail conditions with electric locomotives. The difference between 18 per cent. and 30 per cent. gives the range in tractive effort available for starting on ruling grade and is ample with fair rail conditions.

As the ruling grade existing upon the profile of steam railways does not extend unbroken for distances greatly exceeding 15 to 20 miles, it is possible to proportion the continuous rating of a main-line locomotive for somewhat less than a tractive effort corresponding to 18 per cent. coefficient of adhesion. For example, with modern locomotive motors of the fully ventilated type, it is found that the 1-hr. rating is approximately 25 per cent. more than the continuous rating. Hence, where the ruling grade is short, the average duty

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of the locomotive will be less than would correspond to an 18 per cent coefficient of adhesion. In consequence it is becoming recognised that main-line freight locomotives should be provided with motors capable of supplying continuously and without injurious heating, a tractive effort corresponding to approximately 16 per cent. coefficient of adhesion of the weight upon the drivers, see Par. **266.**

266. Rating of typical slow-speed main-line freight locomotive

Weight on drivers	200,000 lb.
Rated tractive effort, ruling grade	36,000 lb.
Corresponding coefficient of adhesion	18%
Continuous tractive effort	32,000 lb.
Coefficient of adhesion	16%
One hour output	40,000 lb.
Coefficient of adhesion	20%
Starting tractive effort for 5 min	60,000 lb.
Coefficient of adhesion	30%

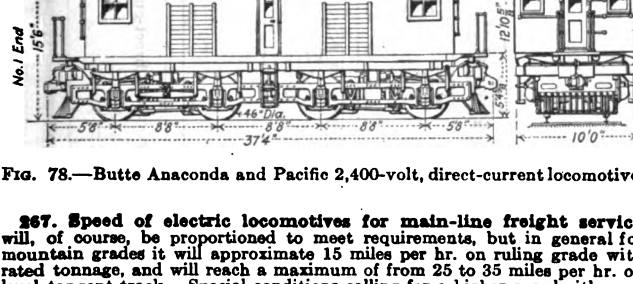


FIG. 78.—Butte Anaconda and Pacific 2,400-volt, direct-current locomotive.

267. Speed of electric locomotives for main-line freight service will, of course, be proportioned to meet requirements, but in general for mountain grades it will approximate 15 miles per hr. on ruling grade with rated tonnage, and will reach a maximum of from 25 to 35 miles per hr. on level tangent track. Special conditions calling for a higher speed either on ruling grade or level track can be met in electric-locomotive design to an almost unlimited extent, due to the flexibility of electric motor construction and control.

268. There are several types of heavy freight locomotives in service:

(a) Those comprising a cab or superstructure containing the control apparatus, air compressor, blowers, operating compartment, etc., mounted permanently on the side frames which carry the drive wheels. The St. Clair Tunnel single-phase locomotive is an example of this type.

(b) Those in which the cab is carried on two bogie trucks which are coupled together by some form of link or hinge coupling. In both this type and the one previously described, the motors are geared to the axle like an ordinary street car motor except that in the case of large motors it is usual to have twin gearing. The Cascade Tunnel three-phase and the Detroit Tunnel direct-current locomotives are examples of this type.

(c) Those in which the cab is carried on two trucks each having two driving axles and one radial or pony axle. The motors are mounted above the axles on the truck frame and geared to quills surrounding the driving axles, the quills being connected to the driving wheels by long helical springs (Fig. **75**). The cab rests on four spring-supported surface plates on each truck. The trucks are coupled together as in (b) so that no draw bar strain is carried by the cab. The New Haven single-phase freight locomotives given in Par. **261**, are of this type. They are also used for heavy passenger service up to 60 miles per hour.

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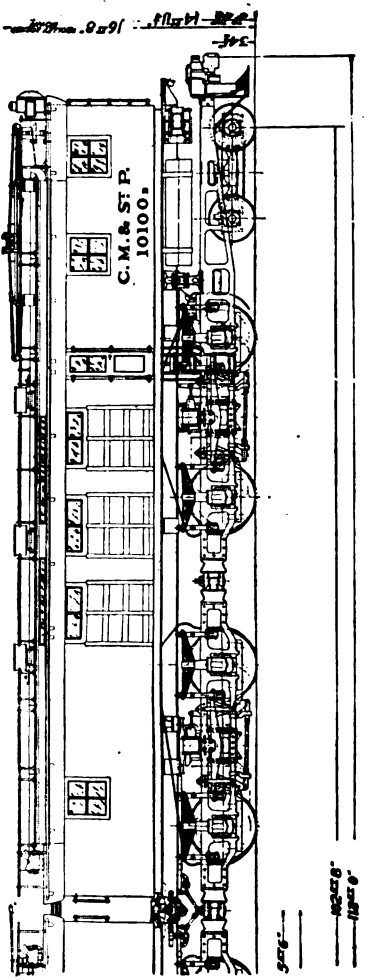


FIG. 79.—Chicago, Milwaukee & St. Paul 3,000-volt direct-current locomotive, "B" half.

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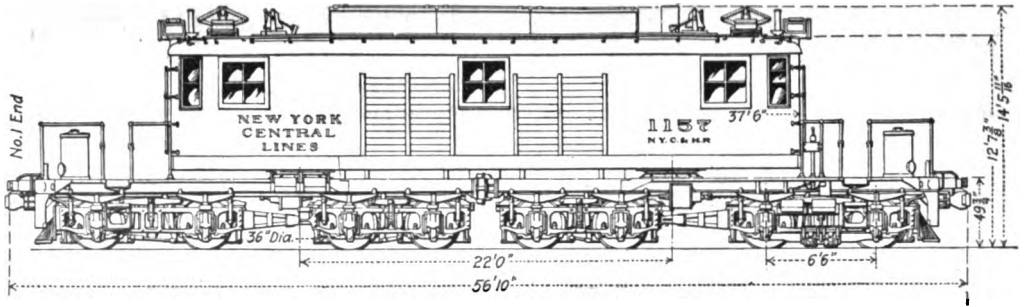


FIG. 80.—New York Central 600-volt, direct-current gearless locomotive (type of 1913, 8 motors).

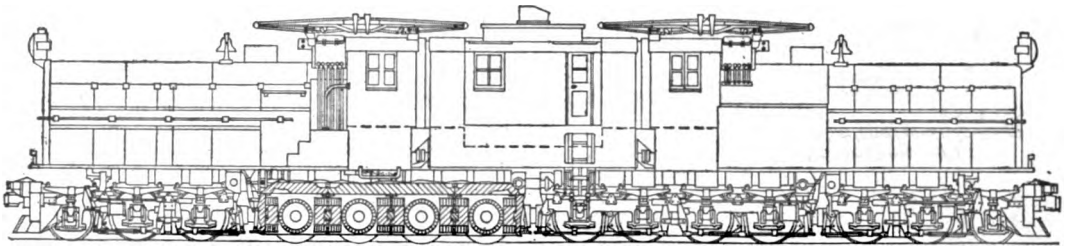


FIG. 81.—Bi-polar passenger locomotive, for 3,000 volts, direct-current, with 12 motors.

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FIG. 82.—Chicago, Milwaukee & St. Paul passenger locomotive, 3,000-volts, direct current, with gear and quill drive.

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(d) Those having cabs mounted on trucks as in (c) but having two motors mounted rigidly between the side frames of each truck, geared to a jack shaft through twin gears, and the jack shaft connected to the driving wheels through side rods. The Norfolk & Western split phase locomotives (see Par. **271**) are of this type.

269. Main-line passenger locomotives are required to operate safely at speeds of 60 to 75 m.p.h. and the heaviest service requires that trailing loads of 1,000 tons be handled at these high speeds in order to meet the requirements.

270. Construction of main-line passenger locomotives. The gearless construction operated upon the New York Central electric zone since 1907 has proved very successful with high operating efficiency and low cost of maintenance. The full advantages of gearless construction can only be realised with direct-current bipolar motors. The original installation of forty-seven locomotives on the New York Central have been supplemented by twenty-six additional locomotives of the gearless direct-current motor type, but with a different wheel arrangement better adapted to higher-speed main-line operation, see Fig. 80.

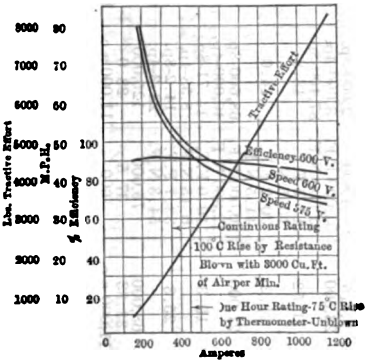


FIG. 83.—Locomotive motor characteristics (N. Y. C., 8-motor, 1913 type).

The latest type of gearless locomotive is a twelve-motor design shown in Fig. 82 for heavy high-speed passenger service over the Cascade Mountains, Chicago, Milwaukee & St. Paul Railway.

Gearless-motor construction provides the simplest form of mechanical drive possible to use, and is well adapted to meet the requirements of high-speed passenger service. For the characteristic curves of a typical direct-current gearless-motor locomotive, see Fig. 83.

The New York, New Haven & Hartford single-phase passenger locomotives are of gearless construction but owing to the fact that the motors are spring supported and the locomotives are free from nosing tendency, they operate safely at speeds of 75 to 80 miles per hour. Forty-one of these locomotives have been in hard service since 1907. They are handicapped by being obliged to operate on 600 volts direct current as well as on single phase alternating current. These locomotives are also notable for the fact that they have field control on direct current, and voltage control on single phase.

The locomotives built for high-speed passenger service over the severe grades of the Rocky Mountain and Cascade Mountain Divisions of the Chicago, Milwaukee and St. Paul Railway, see Fig. 82, are of the latest design of gear and quill drive. These locomotives operate on 3,000 volt direct current. The New York, New Haven and Hartford have also put in service locomotives with this type of drive.

The electric locomotives on the Pennsylvania Terminal electrification in New York (see P. T. & T. locomotive in Par. **271**) are built for the arduous service of taking the heavy trains of steel cars through the tunnels leading to and from the terminal and across the meadows. They regularly haul trailing loads of 800 tons up the 1¼ and 2 per cent. grades at speeds of 30 to 40 miles per hr. These locomotives have established good records for reliability and low cost of maintenance. They have the motors mounted high in the cab thoroughly protected from dust or dirt, and connected to the driving wheels through jack shafts and side rods. See Fig. 84. Field control is also an important feature as will be seen from the table under Par. **271**.

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271. Tabulation of Baldwin-Westinghouse locomotives

Locomotives	N. Y., N. H. & H.	N. Y., N. H. & H.	B. & M. Hoosac Tun.	P. T. & T.*	N. & W.	P. R. R.	C. M. & St. P.
Service	Pass.	Pass.	Frt. & Pass.	Pass.	Frt. 2442	Frt.	Pass.
Type	2442	2.6.2+2.6.2	2442	4444	Three-phase	2.6.0+0.6.2	4.6.2+2.6.4
Type motor	a.c.-d.c.	a.c.-d.c.	a.c. ser. comp.	600 V.d.c.	a.c. 3	a.c. 3	d.c.
Total weight	103	173	130	156	264	258	275
On drivers	81	115	102	100	224	219.5	167.5
Wt. electrical equipment	110,400	174,500	116,000	119,000	224,000	256,000	271,750
Wt. mechanical equipment	94,100	171,500	144,000	193,000	304,000	260,000	278,650
Diameter, drivers, in	62	63	63	72	62	72	68
No. of motors	4	6-double	4	2	8	4	6-double
Type of motor	W-130	409C2	W-403-A	W-315-A	W-450-A	451	348A
One hr. h.p. rating 75 deg. cent.	1,410	2,550	1,510	2,500	3,280	4,800	4,200 h.p.
Contin. h.p. rating 75 deg. cent.	1,125	2,025-hp.	1,415	1,800	2,600-8p.	4,000	3,400 h.p.
Tractive effort 1-hr. rating 75 deg. cent.	9,700	21,000	23,500	31,000 F.F. 21,000 N.F.	3,000-4p. 87,400-8p.	88,000	66,000
Per cent. of weight on drivers	5.98	9.1	11.52	15.5 F.F. 10.5 N.F.	18.8	20.0	19.6
Speed at this tractive effort	54.5	45.6	24.2	30.2 F.F. 44.5 N.F.	14.0	20.5	23.8 M.P.H.
Tractive effort continuous	6,400	14,500	21,000	20,000 F.F. 12,300 N.F.	68,600-8p. 40,000-4p.	73,000	49,000
Per cent. of weight on drivers	3.95	6.3	10.3	10.0 F.F. 6.15 N.F.	14.71-8p. 8.58-4p.	16.7	14.6
Speed at this tractive effort	66.0	52.5	25.3	33.7 F.F. 54.3 N.F.	14.2-8p. 28.3-4p.	20.5	26
Max. guaranteed T.E.	20,000	47,500	68,000	75,000	125,000	146,000	112,000
Per cent. of weight on drivers	12.34	21	33.33	37.5	28.0	33	33
Rated voltage	11,000 a.c. 600 d.c.	11,000 a.c. 600 d.c.	11,000 a.c.	600	11,000 a.c.	11,000 a.c.	3,000 d.c.
Gear ratio	Gearless	27/87	4.13	Gearless	4.72	21/106	24/89
Quantity	41	5	5	33	12	1	10
Date	1912	1919	1911	1910	1914	1917	1920

* Mechanical parts built by P. R. R.

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272. Tabulation of General Electric locomotives

Locomotives	B. A. & P.	Gt. Nor.	B. & O.	D. R. T.	N. Y. C.	C. M. & St. P.	C. M. & St. P.	C. M. & St. P.
Service	Pass.	Frt. 0440	Frt. & pass.	Frt. & pass.	Pass.	Pass.	Frt.	Pass.
Type	0440	Three-	0440	0440	4444	444444	444444	6886
Type motor	2,400 V.d.c.	phase	600 V.d.c.	600 V.d.c.	600 V.d.c.	3,000 V.d.c.	3,000 V.d.c.	3,000 V.d.c.
Total weight	80	115	100	120	125	301	288	265
On drivers	80	115	100	120	125	238	225	229
Wt. electrical equipment	59,800	109,000	65,000	54,180	83,000	274,000	248,000	235,000
Wt. mechanical equipment	100,200	121,000	135,000	185,820	167,000	328,000	328,000	295,000
Diameter, drivers, in.	46	60	50	48	36	52	52	44
No. of motors	4	4	4	4	8	8	8	12
Type of motor	GE-229	GEI-506	GE-209	GE-209	GE-91	GE-253	GE-253	GE-100
One hr. h.p. rating 75 deg. cent.	1,280	1,500	1,100	1,100	2,600	3,440	3,440	3,240
Contin. h.p. rating 75 deg. cent.	1,090	1,400	660	660	2,000	3,000	3,000	2,760
Tractive effort 1-hr. rating 75 deg. cent.	20,200	37,200	24,500	34,400	20,400	45,200	85,000	46,000
Per cent. of weight on drivers	12.6	16.3	12.3	14.3	8.2	9.5	19.0	10.0
Tractive effort continuous	16,500	34,800	12,200	17,200	13,840	38,000	71,000	42,000
Per cent. of weight on drivers	10.3	15.1	6.1	7.2	5.5	8.0	15.8	9.2
Speed at this tractive effort	24.5	15.18	20.1	14.3	54.5	29.6	15.8	25.0
Rated voltage	2,400	6,600	600	600	600	3,000	3,000	3,000
Gear ratio	3.2	4.25	3.25	4.37	Gearless	2.45	4.55	Gearless
Quantity	2	4	4	4	16	12	30	5
Date	1913	1908	1910	1914	1913	1916	1916	1919

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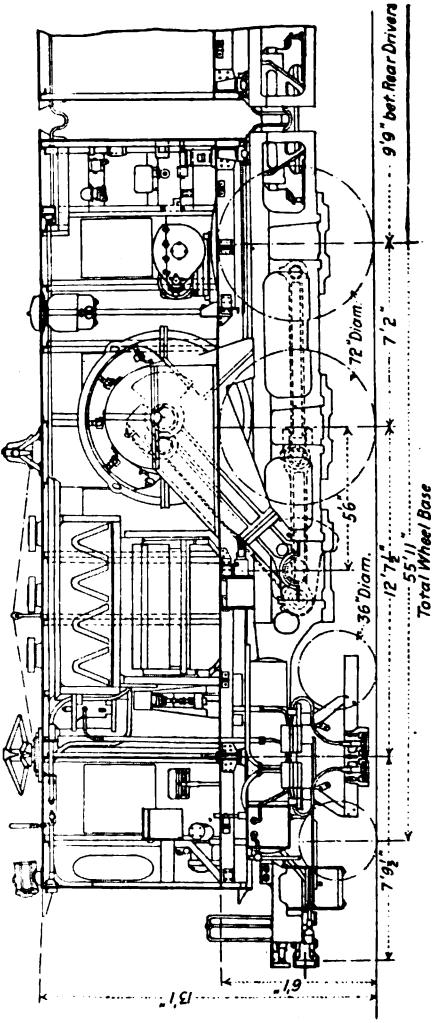


FIG. 84.—Pennsylvania locomotive (cross-section).

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POWER DISTRIBUTION FOR RAILWAY ELECTRIFICATION

273. There are three systems of power distribution that may be considered for the electrification of main line railways, as follows:

(a) Single phase alternating current;
(b) Three phase alternating current;
(c) Direct current.

274. Single phase. One of the prime requisites for main-line electrification is a high voltage for distributing the power from substations to cars and locomotives. This is necessary, first, to minimize the copper in the distributing system; second, to secure maximum efficiency of distribution; third, to simplify the collection of currents for large amounts of power. The use of single phase alternating current permits the use of very high voltages on the trolley—as high in fact as there is any reason for using. In this country the voltages vary from 3,300 and 6,600 which are used on interurban lines and some of the earlier main-line electrifications, to 11,000 which is now accepted as the standard for main lines. In Europe voltages as high as 15,000 are in use, but it is felt in this country that this is higher than necessary. With the exception of one small installation, 25-cycle current is used for all single-phase railways in this country. In Europe, however, the preference is given to 15 or 16⅔ cycles. A frequency of 25 cycles has the advantage of being a standard for power distribution in many localities, and in lower cost of power station and substation apparatus. It has the disadvantage of greater size and weight of commutator-type motors, and thus limiting the output from a given space on a locomotive.

On short single-phase lines the energy may be fed directly from the generators to the trolley, but for long lines, it is necessary to use a high voltage for transmission and feed the trolley from step-down transformers. These transformers are usually located in substations but are sometimes of the outdoor type. In either case regular attendants are not required.

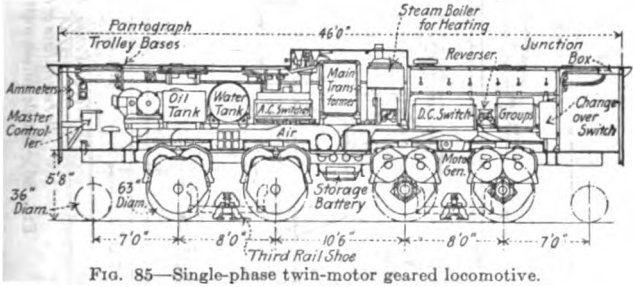


FIG. 85—Single-phase twin-motor geared locomotive.

Two types of equipment are at present operated from single-phase trolleys:

(a) Cars and locomotives having *commutator type motors* with series characteristics;

(b) *Split-phase locomotives* have *induction motors* which derive the additional phases from the phase converter in the locomotive cab. The phase converter consists of a polyphase stator and a squirrel-cage rotor, the combination being in effect an induction motor fed from single-phase supply and getting its polyphase field by means of its rotating armature.

Both types employ step-down transformers on the locomotive so that the motors have low voltages applied to them. The former type is particularly suited for passenger service with both multiple trains and locomotives. It is also well suited for high-speed freight and switching service. In such service the variable speed characteristics are valuable. The split phase locomotive is particularly desirable where heavy grades are encountered which necessitate high tractive efforts and where the automatic regeneration of the motors down grades saves power and decreases the liability of accidents.

The disadvantages attending the use of single-phase current are in the relatively high cost and low efficiency of motive power, the cost of supplying

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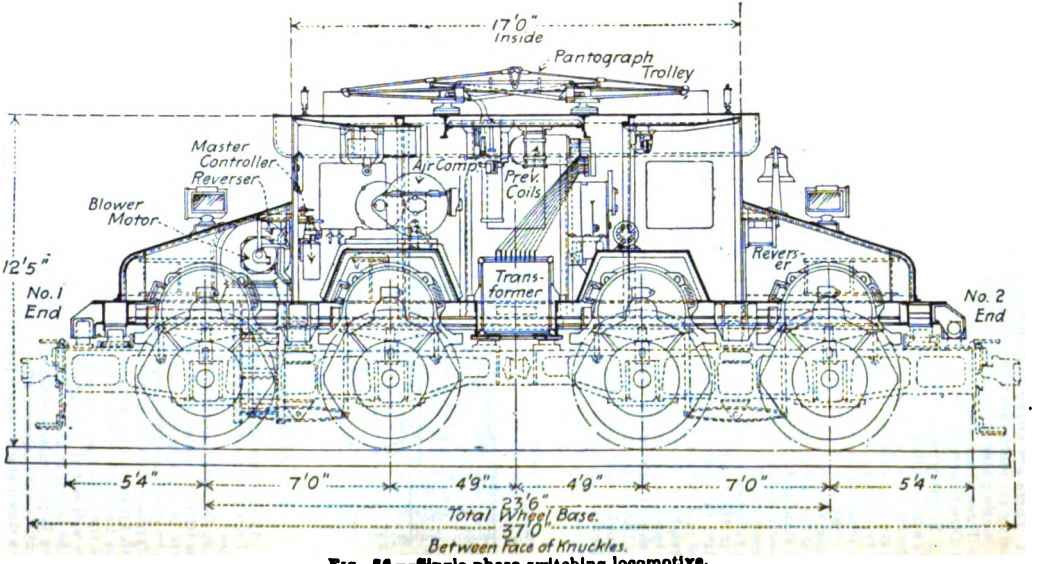


FIG. 56.—Single-phase switching locomotive.

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single-phase power and the inductive interference of the single-phase trolley with neighboring telephone and telegraph circuits. The latter has been largely overcome by the installation of series track transformers, the primary of which carries the trolley current and the secondary is connected in the track return circuit. This has the effect of keeping the return current in the track.

The great advantages of the single-phase system of distribution lie in the high efficiency of the substations and trolley. and the low cost of the distributing system.

Large single-phase locomotives with commutator type motors are in service on the following main line electrifications:

New York, New Haven & Hartford Railway.
Grand Trunk Rwy., St. Clair Tunnel.
Boston and Maine Railway—Hoosac Tunnel.
Spokane and Inland Empire Railway.

This system has also been adopted for the New York, Westchester & Boston Rwy., and the Pennsylvania Railway, both using multiple unit trains, the former for New York and the latter for Philadelphia suburban service.

The Norfolk and Western Rwy. is using split phase locomotives with three-phase motors for heavy mountain grade service. See Par. 271. Liquid rheostats are used in starting these locomotives. The Pennsylvania have also built one split phase locomotive, with which they have been experimenting.

275. Three phase. The three-phase system of distribution is not used to any extent in this country chiefly on account of the difficulties arising from the double overhead trolley which complicates the yards and cross-overs so much. It is used extensively in Italy, and the three-phase locomotives in use there are the lightest electric locomotives of their capacity in the world.

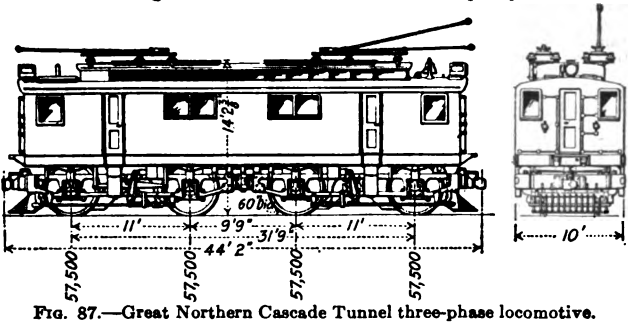


FIG. 87.—Great Northern Cascade Tunnel three-phase locomotive.

Three-phase locomotives are usually used with about 3,300 volts on the trolleys and this voltage is applied to the motors without the use of lowering transformers. The Cascade Tunnel of the Great Northern Railway has the only three-phase locomotives in operation in this country. See Fig. 87.

276. Direct-current electrification consists of a direct-current motor equipment fed from an overhead trolley or third rail which receives power from substations containing rotary converters or motor-generator sets. It is the system in almost universal use in city and interurban electric railways, but varies as to the voltage of the direct-current supply. As a result of perfecting the commutating or interpole motor, it has been possible to wind motors for higher voltages, and 1,500-volt direct-current motors are now in commercial operation. These motors are connected two in series and are fed from a 3,000-volt trolley. Still higher voltage equipments are entirely possible, as indicated by factory experimental apparatus built and tested, and every requirement of the heaviest main-line service can be provided for at moderate cost of locomotives and distribution systems. The chief disadvantage of the direct-current system has been the relatively high cost of feeder copper and substations and their low efficiency but this has been largely overcome by the adoption of higher voltages ar-

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the advent of the automatic substation. The advantages of this system include simplicity, low cost and high efficiency of the locomotives, the option of trolley or third-rail distribution, the benefits of bi-polar gearless-motor construction, and the use of balanced three-phase power supply of any frequency and entailing no serious telephone or telegraph interference.

Large direct-current locomotives are in service upon the following main-line electrifications.

P. R. R. New York Terminal	600 volts
B. & O. Tunnel Railway	600 volts
New York Central Railway	600 volts
Detroit Tunnel Railway	600 volts
Butte, Anaconda & Pacific Railway	2,400 volts
Canadian Northern Railway	2,400 volts
Chicago, Milwaukee & St. Paul Railway	3,000 volts

DISTRIBUTING SYSTEMS

277. Train diagrams represent in graphic form the movement of all trains over a given division during the 24 hr. of operation. Such diagrams are usually plotted with distance as ordinates and elapsed time as abscissæ, and they are of the greatest value in determining the average and maximum sustained demands upon the distributing and generating systems.

The average train input for a given service is determined according to methods outlined in Par. **77** to **117**, so that a train diagram is useful for indicating the local demand upon any part of the distributing system during any period of 24 hr. The train diagram also furnishes means of obtaining the total average load upon the entire division covered by the diagram, by plotting in curve form the total average kilowatts demanded by the several train movements intersecting equally spaced ordinates. Thus, referring to Fig. 88, representing a typical train diagram wherein is depicted the per-

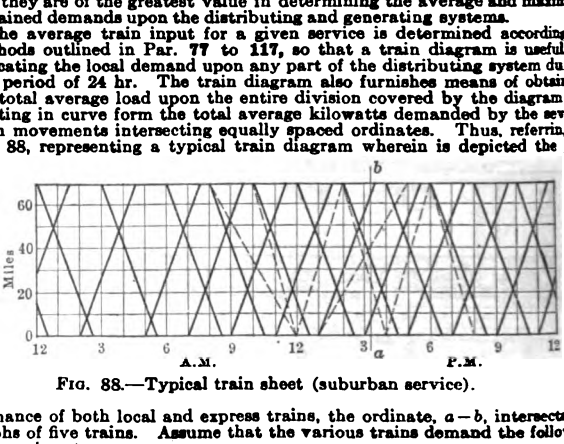


FIG. 88.—Typical train sheet (suburban service).

formance of both local and express trains, the ordinate, $a-b$, intersects the graphs of five trains. Assume that the various trains demand the following average input:

Local passenger	100 kw.
Express passenger	130 kw.
Freight	210 kw.

The line, $a-b$, intersecting the various train movements, therefore, calls for a station output at 3:15 P.M. as follows:

Three local passenger trains	300 kw.
One express passenger train	130 kw.
One freight train	210 kw.
	640 kw.

278. Calculated load curve. By erecting other ordinates upon the 24 hr. performance sheet it becomes possible to plot a detailed generating-station load curve for the 24 hr. with the train movements as predetermined. The train load curve does not show momentary fluctuations, and these must also be considered in determining the character of the distribution system

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especially in suburban and other systems where the train units are large and operate at infrequent intervals.

279. Classification of service. As affecting the distributing system, railway service may be divided into two broad classes as follows: (a) frequent or congested service; (b) infrequent operation. Under class (a) are grouped all city systems, underground or elevated roads and certain suburban roads where the headway between train units is small. Under class (b) are grouped all interurban and most suburban roads, in fact, all classes of service where the interval between trains is fairly large, as 10 min. or more, and where the train unit operates at a high maximum speed and thus demands considerable input. The treatment of classes (a) and (b) service as affecting the distribution system must be somewhat different as in class (a) momentary fluctuations due to starting of cars have little effect upon the size of conductor determined upon for feeders, or location and capacity of substations if these are used In class (b) the momentary input demanded during acceleration is often the determining factor in selecting the amount of feeder conductor and substation capacity required.

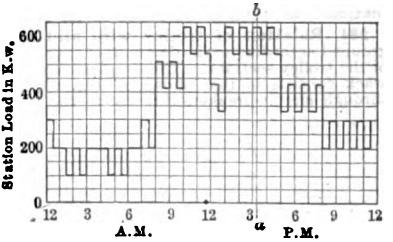


FIG. 89.—Typical load diagram.

280. Classification of distribution systems. Distribution systems may be divided in general into two classes, which are secondary systems (Par. 281), and primary systems (Par. 293).

281. Secondary systems consist of the trolley wire, third rail or other conducting medium, extending from the generating station or substation and the feeders connected thereto; also the track return with its feeders and boosters, if used. The conductivity and physical characteristics of the secondary distributing system are determined partly by the momentary demand of each train unit and partly by the average input required by an aggregation of such units, where the interval between trains is short. For instance, in suburban service a high speed car may be equipped with motors aggregating 300 h.p. to the car, and the conditions of service may demand an input, during acceleration, of 400 kw., while the average input to the car including acceleration, coasting, braking and standing still during stops, may not be much greater than 100 kw. per car. As the train interval is so great that possibly not more than two cars receive power from a substation at one time, it becomes necessary to determine carefully the amount of overload during starting as influencing the conductivity of the distributing circuit and the substation capacity. On the other hand in city service, a substation or generating station may feed fifty or more cars, and individual feeders may carry the load of perhaps fifteen cars, thus, making the momentary demand of any one car a matter of small importance. In such cases the determination of conductivity and substation capacity would rest upon the sum of the average load of all the cars.

282. The permissible drop in voltage of the conducting system between car and bus bar with a specified load, determines its conductivity. This permissible drop varies under different conditions of operation and types of apparatus used. Following are approximate percentages of allowable voltage drop:

City systems	8 per cent. average	12 per cent. maximum
Suburban direct-current systems	10 per cent. average	20 per cent. maximum
Interurban direct-current systems	12 per cent. average	25 per cent. maximum
Interurban alternating-current systems	5 per cent. average	10 per cent. maximum
Three-phase induction-motor systems	5 per cent. average	10 per cent. maximum

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283. The conductance of the circuit between motors and bus bars is seldom determined by its proper relation with interest on first cost of the conducting system and the cost of energy lost, as the first cost of the distribution conductors so determined is considerably in excess of current practice in this respect. In city systems the average and momentary maximum drop are practically the same owing to the small effect of the starting current of any one of the large number of cars controlled by one feeder. In interurban systems, where generally but two cars are controlled by one feeder, the maximum fluctuation is much in excess of the average drop.

284. Relation of trolley wire and feeders. Feeders are differently grouped according to the demands of the service and the physical arrangement of the trolley sections. The simplest conducting system to the car upon the track consists in that shown in Fig. 90, wherein the trolley is connected through circuit-breakers directly to the positive bus bar with no auxiliary

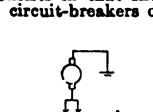


FIG. 90.—No feeders.

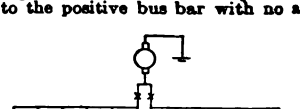


FIG. 91.—Single feeder.

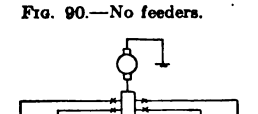


FIG. 92.—Multiple feeders.

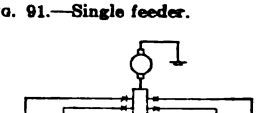


FIG. 93.—Sectionalized trolley wire

feeders, and the negative bus is connected to the track return. The trolley is generally sectioned at the station and each section controlled by an independent feeder panel.

Where the trolley conductor itself has not a sufficiently high conductivity it is reinforced with auxiliary feeders connected to it at frequent intervals. See Fig. 91. The result of such feeder reinforcement is simply to increase the conductivity of the trolley circuit, and corresponds to an enlargement of the cross-section of the trolley conductor itself. This grouping is best fitted for feeding a small number of units, and is more useful in the operation of suburban or interurban systems than in city work.

285. The most economical copper distribution for feeding a large number of train units would consist in a separate feeder to each train so proportioned that the drop in all feeders would be equal to the maximum drop permissible. As this would be impossible without too great a multiplicity of feeders, the arrangement in Fig. 92 is adopted. A better arrangement of the same feeder connection is shown in Fig. 93 which is identical to that in Fig. 92, except that the trolley itself is sectioned so that each feeder independently controls a single section of trolley and the cars drawing energy from that section (Par. **286** and **287**).

286. Length of trolley wire sections. Trolley sections may be from a few hundred yards to 2 miles or more in length in city service, depending upon the lay-out of the streets and the importance of sectionalising different streets or sections of the same street in such manner as to occasion the least possible interruption to general traffic in case of failure of any one trolley section or its feeder.

287. Segregated trolley-wire sections. The trolley wire may be solid throughout as shown in Fig. 92, or preferably sectionalised as shown in Fig. 94, in which case the different sections are entirely independent and each feeder and each trolley section is calculated to give the limiting IR drop when feeding the maximum group of cars drawing energy from that section of the trolley. The direct-current feeder distribution shown in Fig. 93, applied more especially to city systems and may be elaborated to any extent required by the complexity of a large-city trolley system. Sectionalising the trolley is desirable from the standpoint of localising the effect of trolley breaks or

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grounds, and is necessary in large-city systems supplying a considerable number of car units traveling over different routes. Thus, with the sectionalised system, the failure of the trolley on one section will not affect the operation of cars on a different route. The ends of trolley sections should be joined at adjacent ends by a switch or circuit-breaker which normally remains open. This switch may be closed if such procedure be desirable, as in the case of possible failure of an individual trolley feeder. These trolley-pole switches may be operated manually, or they may be controlled electrically from the supply station if they are located at very important points not convenient of access.

288. Feeder copper calculations depends upon the character of the service, trolley potential and permissible drop. In and about cities, 600-volt equipment is universally used, while for suburban and interurban service both 600-volt and 1,200-volt systems are in operation. Still higher direct-current potentials are being proposed, but the 1,200–600-volt combination works out so conveniently in practice that the use of higher voltages will probably be restricted to special locomotive installations.

The use of 1,200 volts direct-current or higher makes it possible to install direct-current generators of this potential and feed direct to the trolley, provided the generating station can be centrally located on a road not over 35 to 40 miles long. One such installation is in operation, and a high efficiency results from the elimination of step-up and step-down transformers, transmission line and synchronous converters.

289. Permanent and booster feeders. City service demands a feeder distribution capable of taking care of rush daily loads without prohibitive drop. In addition a properly proportioned system should easily carry infrequent heavy loads on certain sections such as those due to amusement parks, race courses, etc. The daily rush load justifies the expense of feeder conductor permanently installed, but infrequent loads are best taken care of by feeders arranged for use with series or shunt boosters in the power house. In other words, the infrequent load occurs so seldom that it does not justify the expense of a large amount of feeder conductor, which may be inoperative during the greater portion of the year. With the pyramidal feeder system, Figs. 92 and 93, it is entirely possible to use the outside feeder as a booster feeder in case the infrequent heavy load should occasion a prohibitive drop.

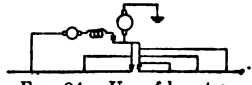


FIG. 94.—Use of booster.

290. Factors determining sectional layout. A city feeder system should be so designed that the voltage of no part of the trolley to ground will be more than 100 volts lower than that at the switchboard when momentary fluctuations due to starting cars are eliminated. This 100-volt average drop should apply to the rush load occurring in daily operation. The laying out of a city direct-current network consists in establishing the limits of the territory controlled by each substation (or generating station if separate stations be used); sectionalizing the district according to routes and streets, determining the average load upon each section as obtained from the average input demanded by the several cars on this section; and determining the cross-section of the conductor required for feeder sufficient to limit the IR drop including track return, to 100 volts. In crowded city districts the trolley will be cut up into such short sections that the additional IR drop occurring therein will not materially add to the combined return track and feeder drop of 100 volts. For the outlying districts less feeder drop must be required, in order to allow for the larger drop occurring in the longer trolley sections. Trolley sections will vary in length, depending upon the density of service, street intersections, etc., ranging from one quarter of a mile up to 2 miles or more in the suburbs.

291. Components of a city distribution system.

(a) **Trolley,** consisting of a grooved copper conductor upheld by so-called cross-suspension approximately 20 ft. to 22 ft. over the centre of the track. This trolley conductor is sectionalized according to local requirements into lengths of from one quarter of a mile to 2 miles or more.

(b) **Feeder system,** consisting of copper conductors extending from the several trolley sections to the supply station. The feeder may be underground in conduits in the congested sections and carried overhead on poles in the suburbs, or in small towns.

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(c) **Booster** in the supply station, which can be connected in series with any feeder extending to a temporarily overloaded section for the purpose of supplying the added voltage required to compensate for the excessive feeder and trolley drop.

(d) **Track return,** consisting of the track rails, bonded at the joints.

(e) **Track return feeders,** consisting of copper conductors reinforcing the track at points of greatest drop or at points where the track is negative to the neighboring pipes.

(f) **Pressure wires** extending to important points on both trolley, track and pipes, and serving to indicate at all times the potential of the several parts of the distribution system.

Such large city systems are a matter of growth and not of calculation, as the practice giving good results in one city may not be directly applicable to the different conditions obtaining in another city.

292. Feeders for underground trolley or conduit systems. Such systems are described in Par. **334.** The trolley conductors are two in number and are located underground between the two rails. These conductors are of opposite polarity, and there is no track return circuit. The arrangement therefore, necessitates double the number of feeders required with the conventionalized overhead trolley used with track return. As both positive and negative rails are insulated from ground, the conduit systems practically eliminate any stray currents and electrolysis. Conduit systems are installed to avoid the unsightliness of the overhead trolley, and can only be considered in the largest cities owing to the enormous expense of their installation.

293. Primary distribution comprises the location of substations and the high-tension overhead transmission lines or underground cables connecting the substations to the generating-station bus bars. Primary transmission systems invariably employ alternating-current, and where synchronous converters or motor-generator sets are used, this primary current is of the three-phase type transmitted over three wires or in multiples of three for duplicate circuits are provided. Owing to the novelty of single-phase railway-motor distribution systems and the close interconnection of secondary and primary distribution systems when applied to alternating-current motor operation, this subject will be considered later (Par. **295**).

294. Methods of serving direct-current substations. Substations for direct-current systems are located at strategic points along the line of travel best suited for secondary distribution. These substations may be fed from a common trunk line to which all substations are connected; this is common practice in suburban and interurban railways operated by direct-current motors. In such cases the trunk line preferably consists of two independent circuits, each of which may be used alone, providing, thereby, for continuity of service in case of the accidental grounding of one set of lines. It is also common practice to interrupt the transmission line at each substation, providing both incoming and outgoing line panels at each substation in order that the transmission-line troubles may be localized between two adjacent subs rather than that a whole trunk line be put out of commission due to the fault of any portion thereof.

In city systems or in interurban systems where the traffic is very heavy and where freedom from interruption of service is of greatest importance it is good practice to connect each substation to the generating-station bus bars through its own individual transmission line or underground cable. In fact, if the substation is very large, this divisibility of the transmission circuit is sometimes carried to the extreme of providing each substation with several cables connected either to individual synchronous converters or to different bus-bar sections. If this bus-bar segregation is resorted to each section is allowed to control two or more synchronous converters. It is evident that this multiplicity of high-tension transmission lines or cables can be made use of only in very large and important cities, or in interurban systems taking care of a very congested traffic.

295. Single-phase generation and transmission. Alternating-current single-phase railway-motor systems are best energized by single-phase generation and transmission, owing to the simplicity of single-phase connections throughout the system. The method of connecting the various alternating-current substations to the generating station consists usually in tying all substations to a single trunk line through circuit-breakers designed to open on short-circuit only. Individual transmission lines

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each substation may be preferable under certain conditions, but multiplicity of transmission circuits is generally to be discouraged owing to the considerable increase in cost over a single or duplicate trunk line.

296. Single-phase generation with three-phase alternators. Owing to the enormous aggregate kilowatt capacity of three-phase 25-cycle generators already in operation for electric railway work, and due to the fact that single-phase railway installations are often an extension of existing direct-current systems, it becomes necessary to consider the different systems of primary distribution for alternating-current roads operating from three-phase generators. The simplest means is to use one leg of the three-phase system for the alternating-current railway distribution, that is, to treat the generator as a single-phase machine and carry out the transmission scheme and substation connections in all respects as though the other two legs of the three-phase generator did not exist. In this case the connections will be as described in Par. **295** for single-phase generators. The objection to this method of connections is the reduction of generator capacity resulting when a three-phase alternator is operated single-phase. For the same heating, the single-phase output of a three-phase generator will approximate two-thirds of its three-phase output on balanced load. Although single-phase distribution is simplest, the resulting reduction in generator capacity may be so serious in certain installations as to necessitate the consideration of three-phase distribution to the transformer substations (Par. **297**).

297. Three-phase transmission "legged" to sectionalized trolley. Where the road is of extended length, the secondary distribution or trolley

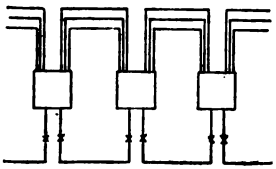


FIG. 95.—Substation systems.

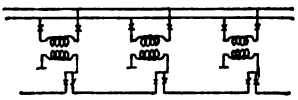


FIG. 96.—Single-phase to trolley.

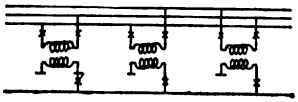


FIG. 97.—Three-phase to trolley.

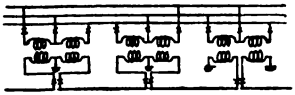


FIG. 98.—Three-phase to single-phase.

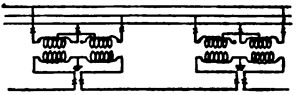


FIG. 99.—Three-phase to two-phase.

circuit may be divided into sections, and each section fed from a separate phase of the three-phase primary-distribution system. This system of connections secures all the benefits of three-phase generation and transmission, provided the load is equally balanced upon the several trolley sections, but requires double the conductivity in the secondary distribution system owing to the impossibility of tying substations solidly together so that trains midway between substations will draw equally on both.

A modification of the three-phase, single-phase, substation connections is shown in Fig. 98, wherein each substation contains two transformers connected in open delta, so that corresponding phases feed each end of a trolley section and each succeeding trolley section will correspond to the different phases of the three-phase primary distribution. This method of connection is often open to the objection that the road may not be of sufficient length to permit of its division into a sufficient number of equally loaded sections to correspond to the three transmission phases or multiple thereof.

298. Three-phase, two-phase transformer connection (Sec. 6) can be used where the road is of limited extent. This method consists

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in employing the three-phase two-phase connection of substation transformer, feeding the two-phases to adjacent trolley sections, so that corresponding phases will be fed to a given trolley section from the transformer substation at its terminals. This system of connections will not provide perfect balance upon the three-phase side of the transformers unless the loads are balanced upon the several trolley sections. Sufficient balancing, however, may be obtained in the majority of cases, and this system of connection is in quite extended use.

299. Two-phase generation and single-phase distribution. Two-phase generators may be used to supply single-phase railway distribution systems by sending out transmission lines from the two phases in different directions, thus amounting in principle to two separate single-phase transmission systems. This method of connection is open to the objection that unless the loads are perfectly balanced upon the two phases, the voltage regulation will be very poor, and in cases of generators having poor inherent regulation, it may reach such proportions as to endanger the lamps and the general operation of the equipments.

300. General considerations in design of a new single-phase motor system. In general a new railway system, favorable for the operation of single-phase motors, operates to best advantage with the single-phase system of generation and transmission, provided the contemplated road has no future connections with neighboring systems and is free from entanglements, such as power distribution, operation of synchronous converters, etc., requiring multiphase generation and distribution. Where it is advisable to provide for the future utilisation of three-phase power, three-phase generators may be installed, operating either on one leg as single-phase generators, or using all three legs in connection with three-phase two-phase transformer connections in the substations in order to provide for reasonably good balancing of the three-phase primary distribution.

301. Three-phase, induction-motor systems may employ the same method of substation connections and primary distribution as outlined under the head of synchronous converter substations for direct-current motor systems. Owing to the fact, however, that transformer substations of all kinds may be operated without attendance, such substations are best connected to a main trunk line through circuit breakers operated by relays designed to open only on short-circuit. Where the control of the substation is extremely important, attendance should be supplied, or each individual substation should be connected to the generating station by separate transmission lines having automatic control at the generating end only. In all cases the trolley or secondary connection to the transformer substation should be safeguarded by automatic switches designed to open on short-circuit.

302. Resistance of trolley wire circuits is dependent upon the weight of trolley copper and track rail, and also upon the composition and bonding of the latter. Trolley conductors are either 000, or 0000 A.W.G., the smallest size being seldom used owing to its lack of strength and the difficulty of clamping its small diameter.

302. Trolley wire and track resistance

Weight of rail (lb. per yd.)	Copper* equivalent (cir. mils)	Ohms per mile					
		Two rails	No. 3/0† trolley	Ohms, total	Two rails	No. 4/0† trolley	Ohms, total
50	500,000	0.056	0.34	0.396	0.056	0.27	0.326
60	600,000	0.047	0.34	0.387	0.047	0.27	0.317
70	700,000	0.040	0.34	0.380	0.040	0.27	0.310
80	800,000	0.035	0.34	0.375	0.035	0.27	0.305
90	900,000	0.031	0.34	0.371	0.031	0.27	0.301
100	1,000,000	0.028	0.34	0.368	0.028	0.27	0.298
110	1,100,000	0.025	0.34	0.365	0.025	0.27	0.295

* Copper equivalent based on steel weighing 490 lb. per cu. ft. and having a resistance 12.5 times the resistance of an equivalent section of copper.
† Resistance for hard-drawn copper.

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304. Impedance. The use of alternating current in the trolley and rail-circuit necessitates some modification in the above values, as the effective resistance is increased by reason of the inductive reactance of both trolley and rail, and also due to eddy currents set up in the rail itself.

305. Rail impedance. The impedance of a rail depends in a considerable degree upon its chemical composition, a reduction in permeability also reducing the internal losses. In general the action is a skin effect, and the impedance and resistance are inversely proportional to the perimeter of the rail and are proportional to the square root of the frequency. This proportion assumes an unbroken rail, and the introduction of short lengths of rail bonded together calls for modifications. Thus at 25 cycles the impedance of track rail of standard outline and composition is approximately eight times the ohmic resistance offered to the passage of direct current; at 15 cycles a ratio of 6.2 obtains, etc. The power-factor at either frequency is approximately 80 per cent. Considering a track circuit with bonding, experimental results show an impedance at 25 cycles of 6.6 times the ohmic resistance.

Under the following conditions the measured impedance of rail of various weights is given below: height of trolley above track, approximately 20 ft.; gage of track standard, 4 ft. 8.5 in.; power-factor of circuit, 80 per cent.; average power-factor of load 80 per cent.; ratio of impedance to ohmic resistance, 6.6 to 1.0; frequency, 25 cycles per sec.

Weight of rail, lb. per yd.	60	70	80	90	100	110
Impedance ohms per mile 2 rails.	0.291	0.251	0.218	0.198	0.179	0.115

306. Trolley-wire impedance. In addition to the increased impedance of the rail itself, the impedance of the overhead trolley conductor is also increased by reason of its reactance when carrying alternating current. Tests made upon 000 and 0000 conductors indicate an increase in impedance 1.5 the ohmic resistance. The conditions under which the following values were obtained were, with the exception of the impedance ratio, the same as those given in Par. 305. Impedance per mile of 000 trolley = 0.495 ohms. Ratio of impedance to ohmic resistance, 1.5. Impedance per mile of 0000 trolley = 0.390 ohms. Ratio of impedance to ohmic resistance, 1.5.

307. The height of trolley-wire above rail can be varied somewhat from the 20 ft. assumed without introducing an appreciable error. The power-factor of 80 per cent. assumed for the load is somewhat lower than would be experienced in a well-proportioned alternating-current railway installation, but the small error of 4 or 5 per cent. introduced by assuming full impedance drop of the trolley and rail circuit is justifiable in making preliminary estimates where the character of load cannot be very closely determined.

308. Classification of trolley construction.

(a) Span construction (Par. 309).
(b) Bracket construction (Par. 311).

309. Span construction comprises poles on either side of the track connected by cable from which is suspended the trolley conductor. The trolley may be hung directly from the span wire through an intermediary insulated hanger or may be suspended from a galvanized steel catenary (Par. 312) which in turn is supported by the span wire. Span construction may be used to provide a support for the trolley wires over any number of tracks. With more than two tracks it is preferable that the side poles shall be self-supporting steel towers joined by very heavy catenary construction, the whole combination being thoroughly anchored to withstand stresses, or else the side towers should be joined by a light steel truss, forming a bridge construction, this latter being used in steam-railroad electrification where the number of tracks exceeds two.

310. Trolley wires generally have a cross-section equal to No. 3/0 or No. 4/0 A.W.G., and are drawn in three sections; round, figure 8, and grooved. The use of round wire is objectionable owing to the difficulty of securely

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clipping it to the hangers without forming a projection on the wire itself which will tend to throw off the current collector in high-speed operation.

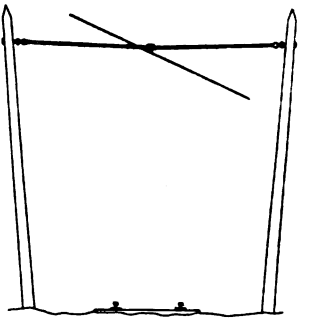


FIG. 100.—Cross suspension.

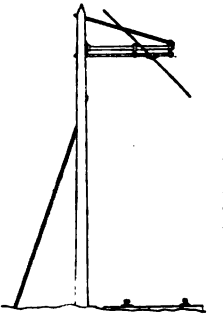


FIG. 101.—Bracket suspension.

The use of figure 8 wire is open to the objection that owing to its unsymmetrical cross-section it is very difficult to handle during installation, although it affords a ready means of fastening and leaves a clear unbroken under-surface suitable for high-speed operation.

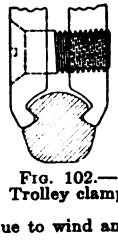


FIG. 102.—Trolley clamp.

The grooved trolley wire (Fig. 102) is in greatest use and consists of a round wire grooved on opposite sides sufficiently deep to permit gripping by adjustable clamps or hangers. Owing to its round cross-section, it is readily unreeled and installed, and presents all the advantages of a smooth under surface.

311. Bracket construction comprises a self-supporting pole having a projecting arm or bracket extending over the track and supporting the trolley wire either directly or by means of a steel catenary cable. The pole is generally of wood, and the best construction provides for anchoring each pole to guard against lateral strain due to wind and the unbalanced weight of the overhung trolley.

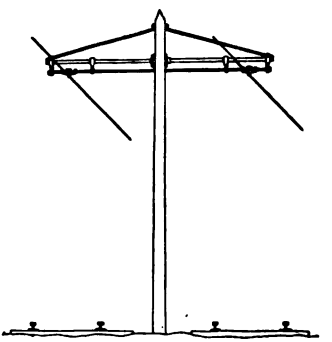


FIG. 103.—Two-track bracket construction.

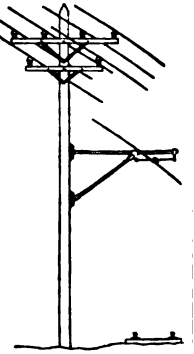


FIG. 104.—Combination po

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The trolley is usually not attached directly to the projecting arm or bracket, but to a flexible cable attached thereto, whose office is to provide for the needed amount of flexibility. Span construction is more flexible than bracket construction, but by use of the flexible bracket cable, the latter can be made sufficiently cushioned to permit the operation of trolley wheels up to 60 miles per hr.

312. Catenary construction (Par. 309) has been brought into prominence with the development of the alternating-current motor, but its application is not confined to alternating-current motor installation as its excellent mechanical qualities are of equal benefit in the case of high-speed direct-current motor installations. Catenary construction comprises either a span or bracket-supporting structure over which is hung a stranded galvanized steel cable loosely suspended with 20 in. or more drop between supports, thus giving rise to the term catenary. From this catenary or messenger cable is suspended the grooved trolley wire by means of hangers of different lengths. The number of these hangers varies from a minimum of three between supports to a maximum of a hanger every 10 ft., the object being to secure a practically flat trolley wire of equal height at all points above the track.

313. Twin trolley construction consisting of two trolley wires hung side by side and alternately suspended from the same messenger was first used on the Chicago, Milwaukee and St. Paul electrification. On account of the fact that there are two trolley wires the current-carrying capacity of the combination is greater than with a single trolley wire and on account of the uniform flexibility of the arrangement there are no hard spots causing the collector to leave the wire and cause arcing. This type of construction is suitable for both high-speed operation and heavy-current collection with pantograph collector.

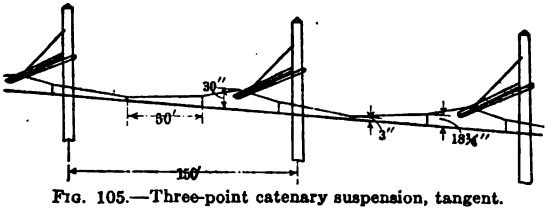


FIG. 105.—Three-point catenary suspension, tangent.

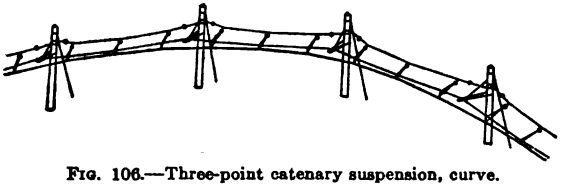


FIG. 106.—Three-point catenary suspension, curve.

314. Advantages of catenary construction. The flexible suspension of a catenary-hung trolley and the flat surface which it presents to the trolley collector makes it admirably suited for the operation of high-speed equipments whether these be of the alternating-current, or direct-current type. This form of construction is furthermore especially adapted to withstand the high-voltage stress of the trolley voltages employed in alternating-current, secondary distribution systems, owing to the fact that the catenary is generally suspended from porcelain insulators of the high-potential transmission type, forming both a strong mechanical structure and having high-pressure resisting qualities.

With catenary construction it is possible to adopt a greater spacing

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between supports than is customary with the self-supporting trolley wire construction.

315. Distance between trolley-wire supports on tangents

Self-supporting trolley	110 ft.
Catenary wooden-pole bracket construction	150 ft.
Catenary steel-pole bracket construction	200 ft.
Catenary steel-bridge construction	300 ft.

The only limit placed upon the distance between supports in catenary construction on tangent track is the likelihood that long spans will have considerable lateral sway. This is corrected in part by suspending the trolley from a double catenary construction, thus forming a triangular truss of considerable rigidity.

316. Pole guying. With wooden-pole bracket construction it is customary to anchor the poles on curves, often on tangents.

317. Duplication of primary circuits. Primary transmission circuits may be carried upon the same poles that serve as a support for the trolley. The transmission line so supported may be supplemented by a separate transmission line hung on independent poles, in order to provide greater assurance for continuity of service.

318. Standard trolley potentials in use are as follows: 600, 1,200, 1,500, 2,400 and 3,000 volts direct-current, 3,300, 6,600 and 11,000 volts alternating-current.

An alternating-current trolley potential of 3,300 volts has been used in several installations but is being superseded by 6,600 volts in the smaller, and 11,000 volts in the larger installations.

319. Overhead collecting devices for use with trolley may be divided into three classes: wheel (Par. **320**), roller (Par. **324**), and sliding-bow (Par. **326**).

320. The trolley wheel consists of a grooved wheel of composition metal ranging from 3.5 in. to 6 in. in diameter, depending upon whether the service is low or high speed. Wheels are carried on a self-lubricating bearing and press against the trolley at pressures from 15 to 40 lb. depending upon the maximum speed of the equipment, this pressure being maintained throughout a wide range in height of trolley wire in order to provide for reduction in standard height of 22 ft. made necessary when going beneath bridges, culverts, etc.

321. Approximate life of trolley wheels

City service 25 miles per hr. maximum	11,000 miles
Suburban service 35 miles per hr. maximum	6,000 miles
Interurban service 50 miles per hr. maximum	3,500 miles
High-speed service 60 miles per hr. maximum	2,000 miles

322. The current capacity of the trolley wheel is determined by its speed and the pressure of contact between wheel and wire, the higher the speed the greater the pressure necessary to maintain contact without arcing. High speed also demands a very nicely balanced wheel and the maximum speed at which trolley wheels are used, corresponds to a car speed of 60 miles per hr.

Following are the current-carrying capacities of trolley wheels at various speeds.

Speed in miles per hr.	5	10	20	30	40	50	60
Current capacity in amperes.	1,000	850	650	550	400	300	200

This table is compiled on the basis of maximum current-carrying capacity at the different speeds with trolley and wheel in good condition. The wheel is balanced for the higher speeds and the contact pressure varies from 20 to 40 lb. between trolley and trolley wheels.

323. Flexible trolley-wire suspension for the higher speeds. For the higher speeds it is absolutely necessary that the trolley suspension be very flexible, preferably hung from a catenary and with the clip fastening the trolley wire of as light weight as possible in order to minimise the blow of the trolley wheel striking it.

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324. Trolley rollers are sometimes used in place of trolley wheels where it is desired to make use of a reversible collecting construction or where the trolley potential is so high as to make it desirable that all control of the trolley collecting devices shall be automatic and not manual with cord. Rolling contacts consist of a brass or composition roller about 5 in. in diameter and 30 in. long, supplemented by stationary wings to provide for greater off-centre displacement of the trolley than can be taken care of by the roller. Roller trolleys are being used for high-voltage direct-current locomotives with success, and improvements in design have made it possible to collect any current required for main-line freight or passenger trains with direct-current 2,400-volt supply.

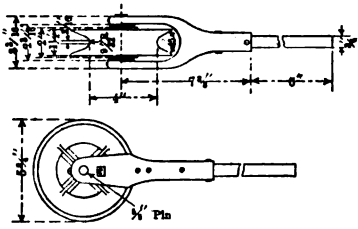


FIG. 107.—No. 12 fork; No. 17 wheel.

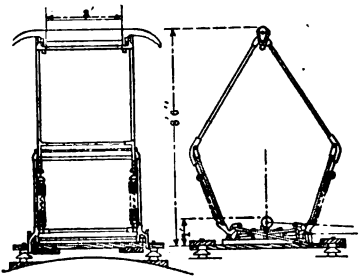


FIG. 108.—Pantograph roller.

325. Sliding shoe trolleys are in very general use at moderate speeds, carrying currents of moderate value, and the development of high potential alternating-current trolley collectors has brought this form of construction into prominence. In many alternating-current roads the use of trolley wheels operated by means of insulated linen cord is still adhered to, but the majority of such roads are adopting some form of roller or sliding-bow contact. As the application of the sliding-bow trolley to high speed operation calls for certain modifications in its construction as hitherto made, no complete operating data are extant in regard to its carrying capacity or its life. For speeds between 50 and 60 miles per hr., the sliding contact has an appreciably less life than either the trolley wheel or roller, but continued use of the sliding bow at these speeds is resulting in the selection of metals and forms of construction which will provide for a reasonably long life. A double-shoe trolley has lately been developed for collecting heavy current which will undoubtedly supersede the roller. It is much lighter and will collect much heavier currents, not only at low but at high speeds.

326. Sliding-bow construction may be supported either by a trolley pole mounted upon a spring base along the lines of standard trolley-wheel construction, or the bow or scraper may be held in a horizontal position at

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all heights by means of the so-called pantograph construction. Because of the parallel motion introduced, it does not interfere with trolley construction.

327. Third-rail construction may be divided into two broad classes: *a*, overrunning contact (Par. 328); *b*, underrunning contact (Par. 334).

Third-rail voltages of 600 and 1,200 volts (Central California Traction) are in operation and still higher potentials are being proposed. The limiting

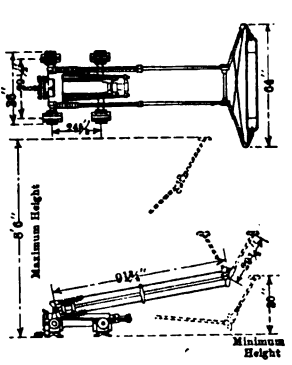


FIG. 109.—Sliding bow.

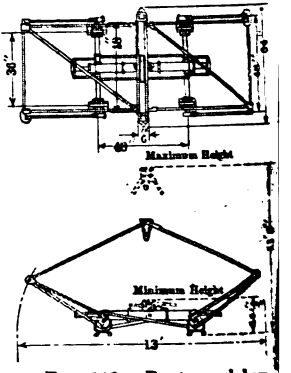


FIG. 110.—Pantograph bow.

third-rail voltage has not yet been reached, and it is probable that the development of improved forms of construction will result in the use of higher voltages for steam-road electrifications. **Bonding** of the third-rail is treated in Par. 349.

328. Overrunning-contact third rails were the first introduced and are in more general use. The construction consists essentially in supporting a steel rail, of either standard track or special composition, upon insulators placed every 10 ft. These insulators rest on supports carried upon projecting ties. Rails are joined loosely by fish plates, are bonded, and at intervals are thoroughly anchored to prevent creepage. Contact is made with the collecting surface of the rail by means of a third-rail shoe suspended from the trucks of the car or locomotive.

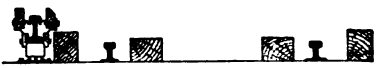


FIG. 111.—Unprotected third-rail.



FIG. 112.—Protected third-rail.

329. Protected third-rail construction is a modification of the above, and consists in providing a wooden or metal shield over the rail in order to protect it from snow and sleet or accidental contact, the rest of the construction being identical with that outlined above. The wood or iron construction is supported by uprights placed every 10 ft. or more, and such protection is usually substantial enough to bear the weight of a man midway between supports.

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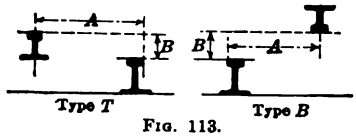


FIG. 113.

330. Third-rail roads giving location of third-rail

Name of road	Type*	Inches on Fig. 113	
		A	B
Albany & Hudson R.R. Co.	U.T.	26.25	6.00
Aurora, Elgin and Chicago R.R. Co.	U.T.	20.25	6.25
Baltimore & Ohio R.R. Co.	P.T.[1]	30.35	3.50
Berlin Elevated and Underground	—	14.375	7.05
Boston Elevated Ry. Co.	P.T.[2]	20.407	5.94
Brooklyn Rapid Transit	U.T.	20.50	6.00
Central London	—	Centre	1.50
Central Calif., Traction Co.	P.B.	29.50	3.00
Grand Rapids, Grand Haven & Muskegon Ry. Co.	U.T.	19.00	6.00
Interboro Rapid Transit Co.			
Manhattan Elevated	P.T.[3]	20.75	7.50
Subway, East side, Viaduct & West Farms	U.T.	20.75	7.50
Subway, all excepting above division	P.T.[4]	26.00	4.00
Lackawanna & Wyoming Valley Rapid Transit Co.	U.T.	20.344	3.00
Liverpool Overhead Railway	—	Centre	1.50
Long Island R.R. Co.	P.T.	27.50	3.50
Mersey Railway	—	22.00	4.50
Metropolitan & District	—	16.00	3.00
Metropolitan West Side Elevated Ry. Co.	U.T.	20.50	11.25
Michigan United Rys. Co.	U.T.	21.50	6.00
Milan-Gallarate	—	26.625	7.50
New York Central & Hudson River R.R.	P.B.	28.25	2.75
Northern Electric Co.	U.T.	25.50	5.562
Northeastern	—	19.25	3.25
Paris-Orleans	—	25.625	7.125
Philadelphia Rapid Transit Co.	P.B.	27.00	
Philadelphia & Western Ry. Co.	P.B.[5]	27.50	5.75
Puget Sound Elec. Ry. Co.	U.T.	21.22	7.125
Scioto Valley Traction Co.	U.T.	28.00	6.00
South Side Elevated Ry. Co.	U.T.	20.125	11.562
Union Elevated R.R.	U.T.	20.125	6.187
Waterloo City	—	28.25	0
West Jersey & Seashore	U.T.	27.344	3.50
West Shore	—	32.00	2.75
Wilkesbarre & Hazleton Ry. Co.	P.T.	28.00	5.00

* NOTE.—U.T. = unprotected top running; P.T. = protected top running; P.B. = protected bottom running.

331. The location of the third-rail is determined by physical characteristics of the rail and by the character of the rolling stock passing over it, that is, sufficient clearance must be provided to allow the passage of low-pressure locomotive cylinders, hopper cars, etc., and also the third rail must be laid

[1] Two side guards and slotted covering through stations.
[2] One side guard on outside 6.25 in. distant, extending 6.5 in. above top of rail.
[3] One side guard on outside.
[4] Like that shown in Fig. 113 "Protected."
[5] Farhan System.

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to provide sufficient clearance through tunnels, etc. The distance from track gage line to centre of third-rail varies from 20 in. to 28 in. and the height above track is from zero inches to nearly 8 in. The smaller distances apply to elevated and subway roads operating only one class of rolling stock, and the greater distances apply to interurban lines or electrified steam lines where provision must be made for the passage of all classes of freight cars and possible steam locomotives.

332. Third-rail jumpers are used to connect the third rail severed at crossings and consist of copper cables bonded to the rail and extending through underground conduits. Jumper cables are heavily insulated, are lead covered, and enter the ground through solidly-constructed concrete structures.

333. Third-rail insulators consist either of impregnated wooden blocks, reconstructed granite or porcelain insulators designed to be held in chairs fastened to elongated ties and forming a loose support for the third rail. In order to provide for elongation of third rail caused by extremes in temperature there is no solid fastening between the third rail and its insulating support, and jumpers must be of sufficient length to allow for creepage.

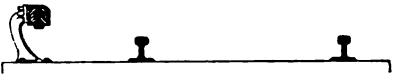


FIG. 114.—Underrunning third-rail.

334. Underrunning third-rails of the protected type, first installed on the New York Central R.R., offer some advantage over the overrunning type in regard to better protection against accidental contact and against sleet and snow. The contact surface being the under side, is self cleaning, and this form of third rail has successfully operated through heavy snow completely covering the third-rail structure. The Central California Traction Co. operates an underrunning third-rail at 1,200 volts.

335. Leakage from third-rail is extremely small and may be neglected unless the road bed should be deeply impregnated with salt. Even though the third-rail be covered with snow it is found that the leakage is too small to constitute a noticeable item of expense.

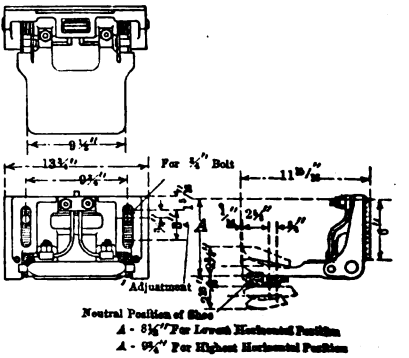


FIG. 115.—Shoe for standard and inverted rail.

336. Third-rail shoes (Par. 337) are of two general types: those acquiring their pressure by gravity and those actuated by means of springs. The unprotected overrunning third rail was first used in conjunction with gravity shoes, and in many installations this form of shoe is still in operation. Where rails are protected it is necessary to provide a form of shoe which will operate

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in the limited space between rail and protection, and such shoes are hinged and actuated by springs in order to provide the necessary pressure.

337. Current capacity of third-rail shoes is much in excess of that of any form of overhead current collector, especially in regard to current capacity at high speeds. Tests have been made which indicate that electricity may be collected at the rate of 2,000 amp. from a single shoe at a speed of 35 miles per hr., and 500 amperes at a speed of 70 miles per hr. Owing to the considerable wearing surface of a cast-iron shoe its life may be taken as exceeding 25,000 miles.

338. Conductivity of the third rail depends upon its composition, and it is sometimes the practice to roll third rails of special composition in order to increase their conductivity. The specific resistance of steel has been found to be proportional to the per cent. of manganese and carbon which it contains. Of these two elements manganese is the most objectionable, and the standard track rail contains from 0.40 to 0.50 per cent. carbon and as high as 0.70 per cent. manganese, which gives it a specific resistance ranging from ten to twelve times that of pure copper. For samples of special construction see Par. **339**.

339. Composition of special third rails

Material	Manhattan railway	New York subway	Albany and Hudson
	Per cent.	Per cent.	Per cent.
Carbon	0.073	0.10	0.090
Manganese	0.340	0.60	0.440
Sulphur	0.073	0.05	0.08
Phosphorus	0.069	0.10	0.088
Ratio of resistance compared to copper	7.7	8.0	7.25

340. Suggested third-rail composition specification

Carbon not to exceed ..... 0.12 per cent.
Manganese not to exceed ..... 0.40 per cent.
Sulphur not to exceed ..... 0.05 per cent.
Phosphorus not to exceed ..... 0.10 per cent.

The resistance of a third-rail of composition given above will be approximately seven and three-quarters times that of commercial copper.

Including bonds, the table given in Par. **341** is representative of third-rail rolled according to these specifications for special rail, having 7.75 times the resistance of copper and of track rail having 12.5 times the resistance of copper.

341. Resistance of rails including bonds

Weight of rail lb. per yd	40	50	60	70	80	90	100	110
Third-rail resistance ohms per mile	0.093	0.074	0.062	0.053	0.046	0.042	0.038	0.034
Two track rails, resistance ohms per mile	0.070	0.056	0.047	0.040	0.035	0.031	0.028	0.025

This table is based upon the use of 9-in. bonds having a carrying capacity equal to one-half that of the rail.

342. Third-rail maintenance is a very small item, as tests have shown the rail to wear an extremely small amount, even in very heavy service. Tests taken show that the passage of 2,000,000 third-rail shoes resulted in wearing away 0.006 in. of special soft rail. The maintenance of a third-rail includes such items of expense as maintaining the bonding, alignment, and insulators in good condition together with the upkeep of jumpers and the cables. This expense has been found in practice to be very small and the low maintenance charge of third-rails together with the possibility

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which such a system offers for handling unlimited current values at any speed constitute the strongest arguments in favor of its adoption.

343. Protection of third rail against sleet and snow is affected directly by the various forms of protected third rail, and it has been found that especially the underrunning type can operate in snow entirely surrounding the third rail without difficulty, owing to the fact that the under contact surface of the rail is self cleaning. With the various forms of exposed overrunning rail it has been found that the accumulation of sleet may be prevented by the use of calcium chloride mixed with water in the proportion of 1 lb. to 5 gal. and sprayed upon the rail at intervals of not more than 2 hr. during the continuance of the storm.

344. Underground trolley or conduit systems are in use only in the very largest cities owing to the enormous expense of their installation. Such systems consist in the location of two third-rails or conductors placed in a conduit located between the track rails, contact being established by means of a plough extending through a slot opening of the conduit. As the plough carries both the positive and negative contacts, there is no track return and hence the conductivity of the track as a return feeder is lost.

Underground trolley systems are installed in city streets where the congestion of travel is sufficiently heavy to warrant the large expense and where the use of overhead wires is objectionable. As conduit systems are essentially double-trolley systems, the feeder network is double that required for an overhead trolley with track return. Both conductor rails are controlled by separate feeders and are divided into sections as previously indicated for city trolley systems. Each section, with its feeders, is controlled by double-throw switches so that it may be made either positive or negative at will. With this arrangement of double-throw switches it becomes possible to throw all temporarily grounded sections on a bus of the same polarity and thus prevent possible short-circuits due to simultaneous grounding of a positive and a negative conduit conductor.

345. Double-trolley systems are installed to a very limited extent in city streets in order to prevent any liability to electrolysis possible with the single-trolley track-return system (Par. 450). Such systems call for double collectors and double-trolley construction, which becomes complicated and expensive to maintain in city streets. One trolley is positive and the other negative, so that the track is not utilised for return and hence need not be bonded.

346. Three-phase double-trolley systems or double third-rail systems are sometimes used in conjunction with three-phase induction motor equipments requiring three conductors, in which case the track acts as the third leg of the triangle. Such systems usually carry several thousand volts upon the trolley wires, employ the catenary overhead construction and are as yet in very limited use.

347. Three-wire systems comprise two overhead trolleys having a potential difference of 1,200 volts between them and 600 volts each to ground. In this case the car equipment consists of two separate 600-volt motor equipments including control, connection being established with the track as a neutral. Such systems can therefore operate either as 600-volt from either or both trolleys, or as a straight 1,200-volt system trolley-to-trolley with the track acting as a neutral and carrying practically no current. Where there is no restriction placed upon the voltage drop in track return such systems suffer in comparative first cost with the single-trolley system.

348. Track return. It is almost the universal custom in electric railway systems to utilise one or both rails of the tracks as a return circuit to the generating station. It was early found that the ground itself or even adjacent bodies of water constituted a return circuit of such high resistance as to be of little practical use, hence the necessity for a carefully bonded track-return circuit, reinforced by feeders where necessary. Data on conductivity and the resistance of standard rails is given in Par. 338 and 341.

349. Rail bonding (Par. 350 to 364) consists in establishing contact from rail to rail, in order to utilise to the fullest extent the conductivity of the rail as a return circuit or as a third-rail. The contact resistance of fish plates is so great as to amount practically to an open circuit, hence the need of a bond of good conductivity. The question of bonding has largely resolved

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itself into the mechanical problem of maintaining a low resistance contact that will withstand the constant pounding and extreme changes in temperature to which the joint is subjected under operating conditions.

350. Types of bonds may be listed as follows: *a*, expanded-terminal bonds (Par. **351**); *b*, soldered, brazed or welded bonds (Par. **352**); *c*, amalgam bonds (Par. **360**); *d*, cast welding (Par. **362**); *e*, electric welding (Par. **364**); *f*, thermit welding (Par. **363**).

351. Expanded-terminal bonds comprise all those which depend upon expanding a soft copper core into contact with the rail through a hole in the web or flange. The size of hole in the rail varies with the capacity and type of bond used, ranging from ⅛ of an in. to 1 in. in diameter. There are two general types of expanded terminal bonds.

The **steel-core bond** comprises a soft steel centre inserted in a copper head and so designed that when placed in the rail and pressure applied, the expansion of the steel core centre will force the copper head into close contact with the rail. This type of bond has been largely superseded by the all-copper bond.

The second type of expanded-terminal bond comprises two solid copper heads or terminals into which is forged a laminated copper conductor joining the two. When the bond is in place and pressure applied, the soft copper head is expanded into close contact with the rail.

Bonds of the expanded-terminal type are designed for use either beneath the fish plate or under the flange of the rail, or are made of sufficient length to span the fish plate. Where the conductor joining the terminals is of considerable length as in cross bonding, it is sometimes made of solid copper wire, but a stranded or laminated conductor is absolutely necessary where the bond is short and must conform to rail deflection at the joint.

352. Soldered bonds have been introduced successfully in some cases. These comprise a laminated copper conductor terminating in two solid heads joined to the rail by soldering, brazing or welding. The bond is attached to the head of the rail on the outside, or to the flange of the rail. In either case it is exposed to view, which facilitates inspection and renewals but also renders the bond liable to theft. It is difficult to obtain a contact by soldering that will withstand constant vibration, but brazed and welded bonds appear to be freer from this objection. Where good contact can be secured the accessibility and cheapness of this method of bonding recommends it.

353. Comparison of soldered and expanded-terminal bonds. Both the expanded terminal and soldered bonds are universally used for bonding the track and third-rail of city and interurban electric-railway systems. While the soldered bond is cheaper and has many qualities recommending its adoption, its use on T-rails laid on surface ties is open to the objection that it is relatively easy of removal which renders it liable to theft. Hence the expanded terminal bond, placed beneath the fish plate is preferable when the rail is exposed.

354. The selection of bonding for a given road depends both upon current capacity and contact resistance desired, and is determined by the class of service involved.

355. The contact resistance of a single 2-in. 4/0 bond of the expanded-terminal type in good condition, is approximately 0.00003 ohms. Hence the relative resistance of bonded joints and track itself is approximately as given in Par. **356**.

356. Comparison of track resistance with bond resistance.

1 Mile 70-lb. track (2 rails) of 12.5 times resistance of copper	= 0.0400 ohms
Single bonding 176 joints at 0.000015 ohms (2 rails).....	= 0.0026 ohms
Total per mile of bonded track.....	= 0.0426 ohms

It is evident that the joint resistance of a well-bonded rail is relatively low compared with the total resistance of the rail itself, but the proportion holds only when the bonding is installed and maintained in first class condition.

357. Double bonding is resorted to in many instances in order to insure a path of good conductivity in case of failure of a single bond. Where double bonding is not required to provide additional current capacity in order to keep temperature rise within reasonable limits, it is better engineering to

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install a single bond of sufficient capacity from a temperature rise standpoint and maintain this bonding in good condition. Double bonding is open to the objection that one of the two bonds may give imperfect contact and be practically useless, and such a method of installation usually results in the operation of the road with practically single bonding throughout.

358. Single bonding for suburban roads where the service is infrequent and current demands do not momentarily exceed 1,000 amp., is to be recommended provided rails are frequently cross bonded and all bonded joints are regularly inspected and maintained in their original good condition.

359. The heating of bonds will determine the size and number of bonds to be used on roads over which there is a large volume of traffic, and where the moving units demand a large kilowatt input, such as trains hauled by locomotives, etc. Following are given values of temperature rise at different current strengths:

Current amperes	500	1,000	1,500	2,000	2,500
Temperature rise deg. cent.	10	35	78	135	210

This table of heating constants applies only to bonding exposed to the air and not covered by fish plate, in the latter case the heating will be somewhat increased. The values given in the table apply only to bonds maintaining good contact with the rail. As one of the integral rails composing the track return may become useless owing to failure of a single bond, each rail must be bonded with the prospect of carrying the full return current. The heating of the bond varies approximately proportional with the square of the current value and extremes in temperature are to be avoided owing to the unequal expansion of copper and rail. It is therefore desirable that the greatest conservatism be used in selecting the bonds for a given service. This holds especially true where soldered bonds are concerned, as too high a temperature will melt the connection between rail and bond. Brazed and electrically welded bonds will, of course, withstand a larger current value and higher temperature without danger of falling off.

360. Amalgam bonds have been used with some success, the most modern comprising a spiral spring approximately 1 in. in diameter containing a soft amalgam, the whole being designed to be placed between the thoroughly cleaned fish plate and rail, and held in place by the bolts extending between them. This type of bonding is easy of application and is useful where a concealed bond is desired.

361. Welded joints in general give the greatest satisfaction where it becomes necessary to bond the rail to its full current-carrying capacity as when the bond is called upon to carry a very high value of current. Welding is obtained by three methods: Cast (Par. **362**), electric (Par. **364**), and thermit (Par. **363**).

All forms of welding are necessarily somewhat expensive, and are not well adapted to the requirements of suburban roads, using T rails laid on ties in the open, because of the inability of such joints to allow for rail expansion.

362. Cast welding is secured by pouring the metal in a mould surrounding the rail joint, thoroughly cleaned for the purpose. Such joints will have no expansion, are somewhat likely to crack, and are best suited for use in city streets where the track is held rigidly in place by the pavement.

363. Thermit welding is accomplished in very much the same manner except that a relatively small amount of metal is required. This process is not as yet in very general use.

364. Electric welding at the rail joint is perhaps best secured by welding a steel strap to each rail, the joint not being continuous between strap and rail but maintained at one or two points of contact. Electric welding has proved very satisfactory in the past, and gives good satisfaction where great current-carrying capacity is desired.

SUBSTATIONS

365. General types. Substations named in the order of their development are defined as Hand Operated, Portable and Automatic.

366. Synchronous converters. The use of the synchronous converter for converting three-phase alternating current to 600 volts direct-current is

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almost universal for supply frequencies of both 25 cycles and 60 cycles. The location and capacity of railway substations depends upon the character of the service and local considerations, but the type of apparatus used is similar whether the substations are located in the city to supply many small-car units, or on interurban lines to supply perhaps but one or two high-speed cars or trains of several such cars. Synchronous converters are designed to operate both three-phase and six-phase, depending upon the capacity and the frequency of supply. Also see Sec. 9.

367. Field of application of the compound converter. The use of the compound synchronous converter with series field is restricted more especially to those systems in which the station output is very fluctuating, such as would be experienced in substations feeding suburban and interurban railway systems, or city systems in which heavy trains accelerate at a rapid rate. The compound winding of converters is generally adjusted for flat compounding at 600 volts throughout the range in load, and this is best secured in conjunction with inductive coils placed in series with the transformer secondaries. Artificial inductive reactance is introduced in compound converter substations both in order to secure flat potential on the direct-current side on all loads and unity power-factor on the alternating current side at all loads.

368. The shunt-wound converter may be used to advantage in substations supplying city service lines.

369. Starting of synchronous converters is accomplished by one of three methods, which are as follows: first, direct-current starting through rheostat; second, alternating-current starting by induction motor; third, alternating-current starting from transformer taps. Starting synchronous converters from the alternating-current side with a reduced potential obtained from transformer taps is the recognised method of starting in universal use. The advantages of alternating-current starting are cheapness of installation and a minimum amount of time required to throw the converter into service, no synchronising being necessary (see Sec. 9).

370. Equipment of synchronous converter substations is generally as follows: (a) Incoming primary feeder, provided with disconnecting switches and lightning arresters; (b) high-tension oil switch and current transformer; (c) step-down transformer; (d) synchronous converter; (e) control panels of the hand or automatic type.

371. Ratio of conversion of synchronous converters varies somewhat with the construction of the machine, being in general as follows: three-phase converters, 370 volts alternating-current to 600 volts direct-current; six-phase converters, 430 volts alternating-current to 600 volts direct-current. Machines having long pole arcs have a somewhat higher ratio of conversion than those of shorter pole arcs. In order to provide for the differences in types of machines and also for the varying drops in the primary distribution system to which rotary converter substations are connected, it is customary to provide five primary taps of 2.5 per cent., each in the step-down transformers.

372. Step-down transformers are of several types, as follows: air-blast, self-cooled, oil-cooled and water-cooled. Each of these several types of step-down transformers can be built three-phase or single-phase; in the latter case three transformers are required for either "Y" or delta connection with each converter.

373. Comparison of transformer cooling methods. Air-blast transformers, when used, require the construction of an air chamber over which they are placed and from which they receive air at a pressure of from ½ os. to 1 os. per sq. in. Air is supplied by a duplicate motor-driven fan feeding into the air chamber. This type of transformer is not designed for potentials above 33,000 volts. For higher potentials and for small transformer units oil is resorted to for cooling by a variety of means.

The design of the small self-cooled (oil) transformer is especially adapted to the smaller sizes, owing to its cheapness. For larger sizes it becomes necessary to cool the oil, either by means of a cooling coil placed in the transformer and through which water is circulated, or by providing means of circulating the oil itself through an outside pipe coil, in order to reduce its temperature. In general, oil-cooled transformers in all sizes and at all potentials are preferred to the air-blast type.

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374. The general arrangement of substation apparatus is somewhat similar in all cases, as such buildings are usually designed for the purpose. In general the wiring scheme consists in providing the shortest and most direct path from the incoming primary lines to the outgoing direct-current feeders, and the interior wiring scheme is carried out with the object in view of preventing any crossing of circuits or doubling back upon themselves.

375. Duplicate apparatus in a substation may or may not be installed, depending upon local requirements and is generally omitted from portable and automatic substations. The manufacture of synchronous converters, transformers, and general substation apparatus, has been so far perfected that failures in such apparatus are very infrequent. It is, therefore, quite customary to install substations containing but a single converter and set of transformers. This practice is largely influenced by local requirements of absolute continuity of service, and also by the development of the so-called portable substation, which is now furnished in units as large as 1,000 kw.

376. Portable substations, so-called, comprise a synchronous converter, step-down transformer, and switch-board apparatus, mounted in a box car and intended to be moved from place to place, as occasion demands, thus serving as a reserve to be used in case of failure, or overload of any substation in the system. A compact arrangement of the apparatus involved has been perfected, so that portable units of 1,000 kw. capacity can be constructed. The complement of apparatus is identical with that in the standard substation, and the arrangement provides sufficient room for the operator. As such substations are not intended for any fixed location, they are designed to be connected to an unbroken primary circuit. The converter may be compound-wound and provided with an equalising switch, so that a portable substation may serve as an auxiliary to a stationary substation in case of extreme sustained overload. Portable substations are often automatically controlled.

377. The automatically controlled substation may be defined as one in which the function of starting and connecting the machines to the line whenever there is a demand for power, and finally shutting them down as the demand for power has been satisfied, are all performed in their proper sequence without the assistance of an operator, either locally or from adjacent stations. The automatic equipment does not require a separate alternating-current feeder to each substation and is, therefore, essentially different from a remotely controlled system with separate feeder to each machine, and in which the operation, both of starting and stopping the machines, is performed by an attendant in the station from which the power is supplied. Since attendants are eliminated and the light load losses saved, it is practical to use a relatively large number of substations with consequent improvement in the voltage regulation. Daily visits, supplemented by a careful inspection once a week, or once every two weeks, are recommended. The control has been developed for units as large as 5,000 kw.

378. Wiring diagrams of automatic substations of 1,000-kw. capacity, of both Westinghouse and General Electric design are given below in Fig. 116 and Fig. 117 respectively.

379. Operation of automatic substations. Substations without attendants may be made to start automatically in a number of ways depending upon conditions to be met, but for the most part they function through the agency of some form of remote control, or automatically by means of a voltage relay, which closes its contacts at some predetermined value of reduced trolley voltage. This scheme is followed by the Westinghouse Electric & Manufacturing Co. for starting their automatic substations (see Fig. 116). Circuits thus set up cause other control relays to function in such a way as to close the oil circuit breaker, the normal field switch and the alternating-current starting switch. Synchronism and polarity are indicated by a polarized motor relay which, in case of reverse polarity, causes the polarity of the machine to be corrected by field reversal accomplished by normal and reverse field switches which open and close automatically. The control for the field switches consists of a small direct-current magnet switch energized from the direct-current end of the converter through contacts made on a small drum switch driven in a counter clock-wise direction by the polarised motor. The field of the polarised motor relay is fixed by means of a permanent magnet, while the polarity of the relay armature be

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comes that of the machine, for the reason that, during starting, it is directly connected across the direct-current terminals of the converter. It is thus obvious that the relay armature will not rotate until the machine has pulled into step, since prior to synchronism it is receiving alternating current of a

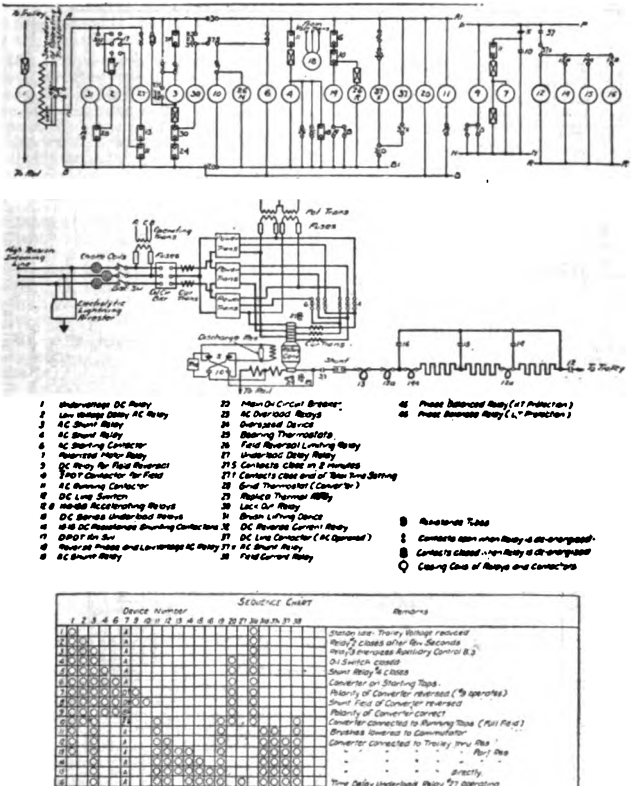


FIG. 116.—Schematic diagram of control for 500 kw. self-starting synchronous converter.

diminishing frequency, the value of which becomes zero at the instant the converter armature reaches synchronous speed. The General Electric Company's automatic substation system performs the function outlined in Par. 377, and protective devices are provided against overspeed, undervoltage, single-phase starting, hot bearings, overheated machines, reverse power, flashover, etc. A motor-driven drum controller is provided to properly time and fix the sequence of operation, thus preventing sneak circuits. The pola-

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of the machine is definitely and instantly fixed by means of a small exciter. The converter is cushioned on the line through load-limiting resistances. This resistance is also used for overload protection. High-speed circuit breakers may be provided for feeder control. A motor mechanism is pro-

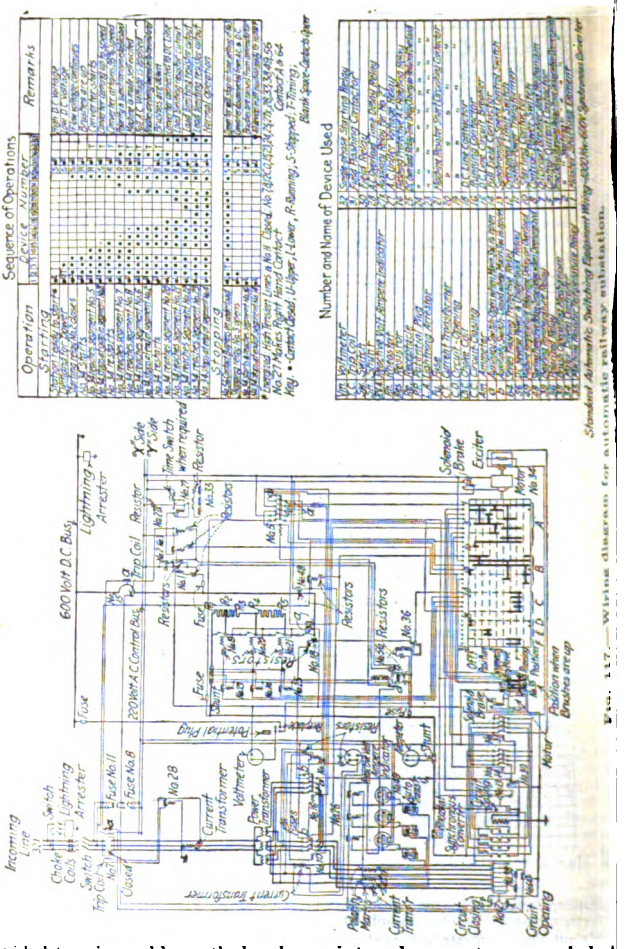


Fig. 117.—Wiring diagram for automatic railway substation.

vided to raise and lower the brushes on interpole converters, as required. A 5-kw. transformer is used to supply energy for operating the control and the oil circuit breakers. A supervisory and remote selective control of the several converters and feeders may be provided, giving the load despatcher instan

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control of the machines, and an answer back to indicate the condition. This control is operated over the usual telephone line. Then through interlocks, which are closed in proper sequence, the brushes are lowered to the commutator by a motor-driven device and the direct-current switches close. This connects the machine to load through current-limiting resistance which is then shunted in steps by switches closed through the functioning of accelerating relays. The machine remains in operation until cut out of service by the light load control.

380. Protective features of automatic substations. Protection is provided by induction type, single and polyphase relays which prevent the station from starting under any abnormal conditions of alternating-current line voltage, such as low voltage, open phase or reverse phase. This same type of relay causes the station to shut down on unbalanced phase conditions; if the trouble is inside of the station, a lockout relay prevents restarting, while if the unbalanced phase condition is outside of the substation, the automatic equipment will function to bring the apparatus into service as soon as the line is restored to normal. Bearings are equipped with thermostats which, in the case of a hot bearing, lock the machine out of service until the contacts of the thermostat device have been reset by hand. A thermal relay protects the machine from overheating on overload. A direct-current reverse current relay, an overspeed device, induction type alternating-current overload relays, a thermostat to prevent overheating of the direct-current current-limiting resistance, and a lockout relay which locks the equipment out of service in case of failure of any part of the apparatus are other protective features.

381. Advantages of automatic substations. The use of automatically controlled substations extends the economic limits of direct-current systems of distribution. The voltage regulation, the efficiency and capacity of a distributing system can be improved by automatically controlled units

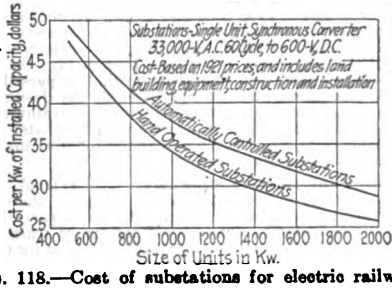


FIG. 118.—Cost of substations for electric railways.

interspaced between existing hand-operated substations. Reserve apparatus in hand-operated stations can be equipped with automatic control and used to great advantage when relocated in these interspaced substations. The advantages claimed for automatic substations are as follows: (1) Reliability; (2) saving of light-load losses; (3) saving in wages of attendants; (4) increase in both normal and overload capacity. Relatively small machines will not be injured when exposed to severe overloads, and this is of importance to electric railways since any number of trains may be blocked near a small substation and started without injury to the apparatus. (5) They permit good voltage regulation with only a small amount of feeder copper; (6) a promising means of electrolysis mitigation; (7) as the number of substations is increased, the chance of an interruption in service caused by the shutdown of a single station is greatly lessened and the need of spare apparatus is also reduced; (8) quick starting in case of load demand. The standard time for starting and taking load is 35 seconds. Quick restarting in case of shutdown due to the interruption of high-tension lines. (9) Relatively small and inexpensive buildings, since no provision need be made for the operator. The relative cost of automatic and manually-operated substations is shown in Fig. 118.

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RAILWAY SIGNALING

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GENERAL

382. Introduction. The development of this art has been and is so rapid that space does not permit either its historical treatment nor consideration of details of design of apparatus or circuits. Little relating to working data or costs is given in this discussion as these change almost from day to day, but only such material as will assist the otherwise well-qualified electrical engineer who may have to do with signaling, to understand some of the principles and practices involved (for further details see Bibliography, Par. **427** to **429**).

383. The salient features of present-day signaling practice are the recognition of the electric track circuit as the only adequate means of signal control, the rapid increase in the use of alternating-current apparatus, and the attention being given to automatic train control.

Interlocking is treated at some length in subsequent paragraphs, because of the lack of information thereon in the publications commonly read by electric railway men, and the increasing electrification of steam roads having yards or junctions requiring its use.

384. Railway signaling may be defined as the art of regulating railway train movements by means of the indications displayed by visual signals of fixed location placed along the roadway. Its practice requires a knowledge of railway operating methods and rules, of train acceleration, running conditions and braking (Par. **203**) and a thorough understanding of the relation of track to traffic. Its function is to prevent loss of life or property from collision or derailment and to save time and money by minimizing congestion and assuring the use of trackage to maximum capacity. Its problems include the proper layout and subdivision of tracks to handle an existing or assumed traffic with the greatest safety and least delay; the determination of the extent to which visual signal indications shall supersede written communication in the regulation of train movements; the design, construction and installation of the necessary signal apparatus; the training of engine and train crews in the understanding and observance of signals; and the organization and training of the necessary personnel for the maintenance and operation of the various installations.

385. Capitulation of railway operation. The tracks of a railroad bear two distinct relations to the trains or cars running thereon, they serve as channels of traffic and they also serve as structures for carrying rolling loads on flanged wheels. In order to define the relations of train movements to each other and to the definite channels of traffic provided by the main tracks and sidings of a railway, rules are established, special instructions issued and time-tables containing train schedules are prepared. These written instructions are supplemented by train orders, communicated from the train despatcher by telegraph or telephone. As the density and particularly the speed of traffic increase to a point where either danger or delay result from the multiplicity of train orders required, it becomes necessary to supply the needed directions for train movement by means less cumbersome and less liable to error. The means usually employed comprise the visual indication of fixed signals (Par. **387** and **388**).

The conditions of the track as a structure, namely, whether the rails are intact and the switches so set that a continuous path for wheels is provided over a given route, can hardly be indicated by rules or written orders but may be readily denoted by signal indications.

386. Classification of railway signaling. Isolated signals are sometimes used to protect particular points such as curves, stations or switches where the view is poor. Train-order signals at stations indicate to trains whether or not there are orders to be delivered. Aside from these two types of installation, signalling naturally divides itself into two classes, namely, *interlocking* (Par. **404** to **420**) and *block signalling* (Par. **421** to **426**).

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TYPES OF FIXED SIGNALS

387. Targets and lamp signals. In American practice, targets of various forms are generally used to show the positions of switches except where the latter are operated from interlocking plants. The signals generally used in interlocking practice, as well as for train-order signals and block signals, are of the **semaphore** type, in which an arm, composed of a casting on which are mounted colored glasses called roundels and a wooden blade, is pivoted about a horizontal axis so that it may be moved either manually or by power, from a horizontal position to an inclined or vertical position in order to indicate the various conditions affecting the movement of trains. All fixed signals, in addition to their day indications, are provided at night with lights of prescribed colors. With semaphore signals, one light is provided for each signal arm and is so placed that as the arm moves to its various positions, the different colored glasses will move in front of the lamp to show red, yellow, green, white or purple light as desired. For block signaling, signals of the enclosed-disc type are used to some extent, although the semaphore affords more distinctive indications.

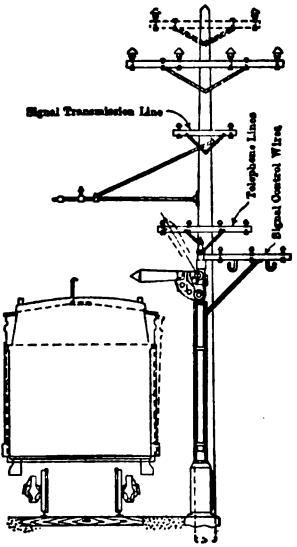


FIG. 119.—Standard location of signal (right of track)

"Light signals," consisting of electric lamps placed behind suitably colored lenses and so shaded as to permit their colors to be distinguished by day, have been introduced to some extent on electric railways, and have been recently developed to considerable efficiency.

The American Electric Railway Association's Committee on block signals has recommended as the preferred type of signals for electric roads, a semaphore moving in the upper left-hand quadrant as viewed from an approaching train; the arm in the horizontal position indicating "Stop;" in the inclined position, 45 deg. upward, indicating "Caution;" and pointing vertically upward, indicating "Proceed." It is considered that less interference with the view of signals by pole lines adjacent to the track will thus result than if the steam railroad practice of displaying the blade to the right of the mast, as seen from an approaching train, is followed. This is based on the American practice of locating signals to the right of the track which they govern (Fig. 119).

388. The usual type of automatic signal is the electric-motor semaphore. The arm comprising the blade and the casting carrying the colored glass roundels is pivoted near the top of the post, the shaft to which it is connected carrying a crank or arm connected to the "up and down" rod placed inside of the tubular iron signal post. The lower end of this rod is connected to the mechanism proper which consists of an electric motor and gearing whereby the motor transmits motion to the up and down rod. A device called a "slot" which comprises a magnet and latch is so arranged that if the magnet is energized the motion of the motor is transmitted to the signal arm, but if the magnet is de-energized, mechanically disconnects the motor from the up and down rod allowing the signal to go to the stop position by gravity. Signal mechanisms of the "top-post" type have the motor mounted adjacent to the semaphore-arm shaft at the top of the post.

The "slot" mechanism is generally provided with two windings in multiple, one of low resistance being in series with the motor while the latter is clear-

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the signal. A circuit controller actuated by the signal arm when the latter has moved to the clear position, opens the circuit of the motor and low resistance winding, leaving the high-resistance coil energized in order to hold the latch carried by its armature. This latch, by connecting the driving and driven members of the "slot," holds the signal in the clear position. The high resistance of the holding coil reduces the current required for holding the signal clear, to a fraction of that required to clear the arm using the motor and the low-resistance coil in series with it. Motor-driven signal mechanisms are of many types and are designed for either upper-quadrant or lower-quadrant movement of the arm; for operating in three positions; or for operating, by selection, one of two or three arms on a post. Motor-driven signal mechanisms are used for operating either black or interlocking signals with direct or alternating current at from 10 to 110 volts.

TROLLEY-OPERATED SIGNAL SYSTEMS

389. Operation and reliability of various systems. On many electric railways the volume of traffic is not sufficient to warrant the expense of employing signalmen to operate manual or controlled-manual block signals. Hence signal systems have been developed which are partly manual and partly automatic. In such systems the manual operations are performed by the motormen or conductors of cars or trains, and the automatic operations are performed by the action of the trolley upon circuit controllers, actuated by the passage of the trolley wheel. A very large variety of signal installations of this character have been made, varying from exceedingly simple ones to those involving a greater complication of apparatus and circuits than are necessary in complete automatic blocking. Many of them are very crude and of decided limitations both as to safety and the extent to which they facilitate traffic. Many of them depend upon step-by-step devices which count the number of cars that enter a block and count them out at the other end of the block. A number of these systems have been quite highly developed as regards their apparatus. The relays and magnets as a rule require no separate source of energy for their operation but use the trolley current. None of them can be considered as offering a degree of safety or reliability approaching systems employing the track circuit, which is the only means so far known in signaling whereby a train is *continuously* active in maintaining its own protection (Par. **392**).

390. Relative value. By strict obedience to the prescribed rules for their observance, without which no signal system is of value, trolley-operated signals afford a very considerable degree of protection and facility to traffic. Their relatively low cost makes them available where other systems could not be installed on account of the expense involved.

391. Tendency toward abandonment. The development of the **light signal** to a point where its day indication can be observed at distances sufficient for stopping high-speed cars, enables it to be substituted for the electric-motor semaphore, resulting in a material reduction in the cost of automatic block-signal systems employing the continuous track circuit. The additional apparatus and line wires which it has been found necessary to add to the trolley-operated signal systems to make them furnish the same information as that given by track-circuit signal has, on the other hand, tended to increase their cost. The costs of the two systems are thus rapidly approaching each other, and the tendency toward the adoption of track-circuit signaling for electric railways is increasing to such an extent that the latter bids fair to supersede the trolley-operated signal at no distant date.

THE TRACK CIRCUIT

392. "A track circuit may be defined as a metallic path for an electric current formed primarily by both rails of a pre-determined length of track, the terminating rails of which are electrically separated from adjacent rails, a source of electric energy for maintaining a difference of potential between the rails; and one or more devices (relays) so connected in the circuit as to respond to variations in the potential difference between the rails produced by train action upon them" (J. P. Coleman). This invention, than which none other has contributed more toward safety and despatch in railway transportation, is to-day the only medium recognized as fundamentally safe by experts in railway signaling, whereby a train or any vehicle thereof

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may retain continuous and direct control of a signal while occupying any portion of the track protected by the signal.

393. The function of the closed track circuit is to maintain a relay normally in an energised state; the influence of the train upon the rails is to de-energize this relay by shunting or short-circuiting the generator, a process as effectively accomplished by a single car as by a train of considerable length. On account of the low insulation resistance between the rails, due to the conductivity of the ties and ballast, track circuits are susceptible to influence from excessive leakage of current from rail to rail. This leakage may approach, in its effect, the value of current conducted by the wheels and axles of a train. Obviously a failure of the source of energy or a break in the circuit, whether in the rails themselves or in the wires connecting the battery or the relay to the rails, produce the same effect upon the relay as if a train were running or standing on the rails. The contacts carried by the armature of the track relay (Fig. 120), which are closed only when the relay is energized, are included in the circuits which control the signals themselves. These circuits must be closed in order that the signals may indicate "proceed." Thus the track circuit conforms to the principle demanded by sound practice, namely, that the signals shall invariably display the "stop" indication when their operating or controlling energies cease to be active from any cause.

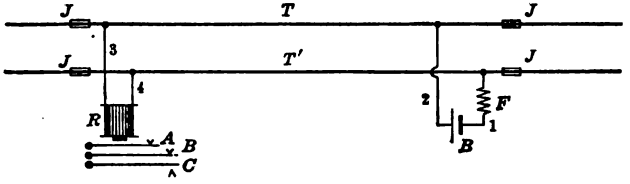


FIG. 120.—Track-circuit.

B, Source of energy, as two gravity-battery cells in multiple, or one storage-battery cell with series resistance F to limit current output when rails are short-circuited by wheels and axles of a car, or a transformer, 2 to 8 volts where alternating current is used. J, Insulated rail joint. T T', The track rails included within the block, adjacent rails being bonded. R, Relay, normally energized by current from B. A B, Contacts carried by armature of relay R and closed when R is energized. C, Contact carried by armature of relay R and closed when armature falls by gravity upon R being de-energised. The path of current is from B through wire 1, resistance F (if used) track rail T', wire 4, magnet coils of relay R, wire 3, track rail T, wire 2 to B. The distributed leakage of current between track rails T and T', through the ties and ballast, is in multiple with relay R.

394. Requisite performance of the electrical equipment. The source of energy supplying current to a track circuit should do so at the least e.m.f. that is practicable. The current capacity should not be excessively great nor yet too limited. When a train is so far advanced within the block from the relay end as to constitute a somewhat imperfect shunt upon the relay, stray currents sometimes find a path through it from adjacent rails through damp or defective rail insulations. Relays should not be sufficiently sensitive to respond to these currents. In excessively long blocks and where the likelihood of such occurrences exist, one of the remedies is to locate a relay at each end of the section and supply current to the centre of the circuit, so that as the shunting effect of the train recedes from one relay it approaches the other. Naturally the resort to this device entails additional cost and complication, for the operating circuit of the signal is carried through the entire block for control by both relays.

395. Low e.m.f. impressed upon track circuits is advantageous for two reasons: first, to minimise the break-down effect of the e.m.f. upon rail joints of defective insulation or upon damp ties and ballast and other parts that afford a normal leakage of current from rail to rail in wet weather; second, to reduce to a minimum the energy normally discharged through

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the road-bed and relay when the track section is unoccupied, as well as to avoid extravagant discharge through the train axles when the section is occupied. Where the common gravity battery is the source of energy, the general custom on steam roads, its internal resistance is sufficient and no external resistance need be provided. On account of the variation in internal resistance with gravity batteries, however, it is more general in present steam railroad practice to use storage batteries with a fixed resistance in series therewith.

396. Track relays. In common steam-railroad practice relays of from 4 to 9 ohms resistance are employed on track circuits varying in length from about 60 ft. as a minimum, to about 6,000 ft. as a maximum. A certain minimum air-gap between the relay armature and its pole pieces must exist in order to prevent undesirable effects from residual magnetism. As this air-gap is increased when the armature falls away under the action of gravity, to permit the contacts carried by it to open, it is evident that more current through the relay will be required to lift the armature than to hold it in position against the pole pieces, once it has been raised. The usual 4-ohm track relay requires about 70-mil amperes through its coils to pick up the armature; it will drop away when the relay is shunted sufficiently to reduce this current flow to about 35 mil-amperes.

While much included in the foregoing paragraphs is only applicable to direct-current track circuits for steam roads, it may be considered important as indicating the principles upon which the track circuit has been developed. These principles should be thoroughly understood by the electrical engineer as a preparation to the consideration of track circuits for electric railways. (Par. **397**).

TRACK CIRCUITS FOR ELECTRIC RAILWAYS

397. Effect of bonding. Wherever, as is the case in most electric railways, adjacent rails of the track are bonded together to form the best possible conductor for the return *propulsion* current, it is obviously impracticable to divide these rails into sections electrically separated from each other by insulated joints, as is done where track circuits are used for signaling on steam railroads, unless means can be provided for the return of the propulsion current without affecting the action of the track-circuit relays. In case the track is laid upon a metallic structure one rail can be bonded to the structure. Other considerations may render one rail of each track sufficient for the return of the propulsion current. One of the rails may therefore be left electrically continuous to serve as a return for the propulsion current, while the other is cut into sections of proper length for the control of the signals. It is evident, if generators and relays are connected across the rails at opposite ends of each track section, that in the event of the conductance of the power rail becoming reduced as a result of defective bonding, the return current would divide so that a sufficient amount of it might flow through the signal relays to energize them even when a considerable shunting effect was produced upon them by a train in the block. Furthermore, the drop in potential, due to the return of power current over the considerable length of rail included within the limits of the block, might be sufficient to energize the track relay illicitly.

398. To prevent improper operation of track relays by differences of potential between the track rails produced by the propulsion current itself, the track relays for electric roads are designed to be immune to the effects of the propulsion current. This may be accomplished either by protecting them against excessive flow of current with series resistance and, in some cases, providing a shunt path around the relay for the propulsion current, or by so designing them that they will respond only to the action of alternating current. Where alternating current is used for propulsion the relays are made to respond only to an alternating current of a different frequency than that used for propulsion.

399. Field of single-rail track-circuit system. Whenever, as in yards or terminals, the number of tracks that can be bonded together is sufficient to afford an adequate return for the propulsion current, one rail of each track being assigned to signaling, the single rail track circuit is used for the return of the propulsion current. Fig. 126 shows a single-rail track circuit as installed at an interlocking plant, with a desirable arrangement of the apparatus.

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400. Impedances and power-factors per 1000 ft. of track

(Union Switch and Signal Co.)

Weight of rail	Bonding	27.5-ft. rails				30-ft. rails				33-ft. rails			
		25 cycles per sec.		60 cycles per sec.		25 cycles per sec.		60 cycles per sec.		25 cycles per sec.		60 cycles per sec.	
		Impedance	Power-factor	Impedance	Power-factor	Impedance	Power-factor	Impedance	Power-factor	Impedance	Power-factor	Impedance	Power-factor
100 lb.	Total capacity	0.10	0.40	0.25	0.40	0.10	0.4	0.25	0.40	0.10	0.40	0.25	0.40
	2 No. 6 copper	0.13	0.72	0.28	0.56	0.13	0.7	0.28	0.56	0.13	0.69	0.27	0.54
	1 No. 8 iron 1 No. 6 copper	0.17	0.83	0.30	0.65	0.16	0.82	0.30	0.63	0.15	0.79	0.29	0.62
	2 No. 6 c.c.–40 per cent.	0.19	0.87	0.30	0.69	0.19	0.86	0.32	0.69	0.17	0.84	0.31	0.68
	2 No. 6 c.c.–30 per cent.	0.25	0.91	0.36	0.75	0.22	0.91	0.35	0.74	0.20	0.88	0.34	0.73
	2 No. 8 iron	0.40	0.97	0.50	0.88	0.36	0.96	0.47	0.87	0.34	0.96	0.44	0.85
90 lb.	Total capacity	0.10	0.43	0.26	0.43	0.10	0.43	0.26	0.43	0.10	0.43	0.26	0.43
	2 No. 6 copper	0.14	0.73	0.29	0.58	0.13	0.72	0.28	0.58	0.13	0.70	0.27	0.54
	1 No. 8 iron 1 No. 6 copper	0.17	0.83	0.31	0.67	0.16	0.82	0.31	0.64	0.16	0.80	0.29	0.62
	2 No. 6 monnot–40 per cent.	0.19	0.87	0.33	0.71	0.19	0.87	0.33	0.70	0.17	0.84	0.31	0.68
	2 No. 6 monnot–30 per cent.	0.23	0.91	0.36	0.76	0.26	0.91	0.36	0.76	0.20	0.89	0.34	0.73
	2 No. 8 iron	0.40	0.97	0.51	0.89	0.37	0.97	0.48	0.88	0.35	0.96	0.45	0.86
85 lb.	Total capacity	0.10	0.46	0.26	0.46	0.10	0.46	0.26	0.46	0.10	0.46	0.26	0.46
	2 No. 6 copper	0.14	0.74	0.29	0.60	0.13	0.73	0.29	0.59	0.13	0.71	0.28	0.58
	1 No. 8 iron 1 No. 6 copper	0.17	0.84	0.32	0.68	0.17	0.83	0.31	0.67	0.16	0.81	0.30	0.65
	2 No. 6 monnot–40 per cent.	0.19	0.88	0.33	0.72	0.19	0.87	0.33	0.69	0.18	0.85	0.32	0.70
	2 No. 6 monnot–30 per cent.	0.23	0.91	0.37	0.77	0.23	0.91	0.36	0.77	0.21	0.89	0.35	0.76
	2 No. 8 iron	0.41	0.97	0.52	0.89	0.37	0.97	0.49	0.88	0.35	0.96	0.46	0.84
80 lb.	Total capacity	0.11	0.48	0.26	0.48	0.10	0.48	0.26	0.48	0.11	0.48	0.26	0.48
	2 No. 6 copper	0.14	0.75	0.29	0.62	0.14	0.73	0.29	0.60	0.13	0.72	0.29	0.60
	1 No. 8 iron 1 No. 6 copper	0.17	0.84	0.32	0.69	0.17	0.84	0.31	0.68	0.16	0.82	0.31	0.67
	2 No. 6 monnot–40 per cent.	0.20	0.88	0.34	0.73	0.20	0.88	0.34	0.73	0.18	0.85	0.33	0.71
	2 No. 6 monnot–30 per cent.	0.23	0.91	0.38	0.78	0.23	0.91	0.37	0.78	0.21	0.89	0.36	0.76
	2 No. 8 iron	0.41	0.97	0.53	0.89	0.37	0.97	0.49	0.88	0.35	0.96	0.47	0.87
70 lb.	Total capacity	0.11	0.52	0.27	0.52	0.11	0.52	0.27	0.52	0.11	0.52	0.27	0.52
	2 No. 6 copper	0.15	0.77	0.30	0.65	0.14	0.76	0.30	0.65	0.14	0.75	0.30	0.64
	1 No. 8 iron 1 No. 6 copper	0.18	0.86	0.33	0.72	0.17	0.85	0.33	0.71	0.17	0.82	0.32	0.70
	2 No. 6 monnot–40 per cent.	0.20	0.89	0.36	0.75	0.20	0.89	0.35	0.75	0.18	0.86	0.34	0.74
	2 No. 6 monnot–30 per cent.	0.24	0.92	0.39	0.80	0.24	0.92	0.38	0.81	0.22	0.90	0.37	0.78
	2 No. 8 iron	0.42	0.97	0.54	0.90	0.38	0.97	0.51	0.89	0.36	0.96	0.48	0.87

Resistance of bond wires	27.5-ft. rails	30-ft. rails	33-ft. rails	
2 No. 6 copper	0.057	0.052	0.048	Bond wires 48 in. long. No allowance is made for conductance by the splices.
1 No. 6 copper and 1 No. 8 iron	0.098	0.089	0.082	
2 No. 6 monnot–40 per cent.	0.124	0.112	0.103	
2 No. 6 monnot–30 per cent.	0.166	0.150	0.138	
2 No. 8 iron	0.348	0.315	0.291	

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401. Two-rail track-circuit system. Where it is not practicable to give up one of the track rails for signaling purposes, the conditions existing in the single-rail track circuit not only apply, but means must also be provided whereby both rails are electrically continuous for the return of the propulsion current, but are electrically separated from adjacent rails at the ends of each track section in so far as the signaling track-circuit current is concerned. This is accomplished through the means of **impedance bonds** which consist of a few turns of heavy copper wound about and insulated from a laminated-iron core. The connections of impedance bonds to the rails is so made that the traction current has no magnetic effect on the bond, provided an equal amount of current is flowing in each of the rails. If, however, more current is flowing in one rail than in the other, there will be a tendency to saturate the iron core and thereby reduce the impedance of the bond. This effect, which is called "unbalancing," is limited by introducing an air-gap into the magnetic circuit, the bonds ordinarily being designed to stand 20 per cent. unbalancing without a decrease of more than 10 per cent. in impedance. The size of the bond to be installed is dependent upon the amount of current it will be obliged to carry, the impedance for which it must be wound (this being more or less dependent upon the length of the track circuit) and the amount of unbalancing to be cared for. Where good traction bonding can be maintained, unbalancing can be assumed less, hence a smaller size of bond can be employed.

402. Energy supply for signal system. Power for the operation of the track circuits and signals on an electric railroad may be taken from transformers connected directly to the propulsion-power transmission system. More frequently a signal-power line is provided to furnish this current at a reduced voltage, the necessary apparatus being located in the substations. For the track circuits, the potentials of the transformer secondaries range from 2 to 8 volts, and for the operation of the signals and line circuits generally from 55 to 110 volts. For any installation it is necessary to construct a power diagram. The current consumption of the track circuits, relays, alternating-current signal motors, indicators, lights, etc., will vary in each installation and will be affected to some extent by the volume of traffic which governs the number of switch and signal movements per day. The energy consumption data for each piece of apparatus is furnished by the maker.

403. Track-circuit constants. The data in Par. **400** show the impedance in ohms per 1,000 ft. of track and the power-factor of steel rail of various weights and lengths for frequencies of 24 and 60 cycles and with various types of bonding. In all electric-railway practice the current-carrying capacity of the bonds provided would be assumed equal to that of the rail itself. The data given for the other types of bonds apply to single-rail circuits for electric roads or to steam-railroad conditions.

INTERLOCKING

404. Definition and field of application. Interlocking plants are assemblages of switches, switch-operating and switch-locking devices, and signals so interconnected that their movements must succeed one another in a predetermined order. They are used at crossings or junctions of one line with another, at drawbridges, at cross-overs, or in yards where the number of switches or the frequency of their movement is so great that hand operation would not be sufficiently rapid nor safe. At railroad crossings or drawbridges, signals are frequently interlocked with derailing devices, this protection being required by the laws of several states provided trains are permitted to pass over without stopping.

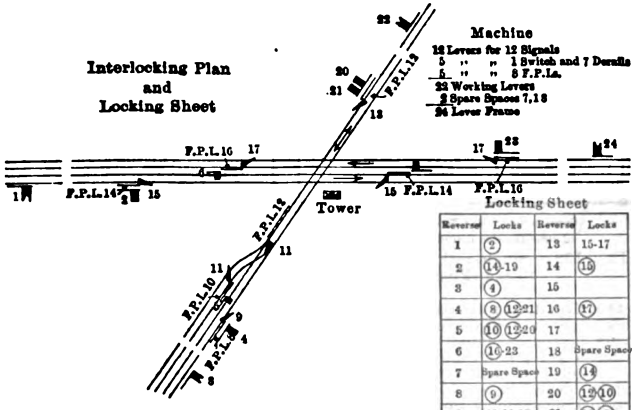
405. Classification. Interlocking plants are either mechanical or power-operated. In those of the former type, pipes or wires connect the switches, locks, signals, or other operated units with the levers that operate them. In the latter type, pneumatic cylinders or electric motors are connected to suitable "lock and switch movements" or signal mechanisms. Electric circuits controlled by the levers in the interlocking machine regulate the operation of these switch and signal mechanisms.

406. Mechanical processes involved in interlocking. In all interlocking machines the desired sequence of operations is secured by means of the

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dogs, bars, or tappets which constitute the mechanical locking. These parts are so interrelated that if any lever in the machine is reversed (that is, moved from its normal position), the act of the signalman in unlatching this lever will cause parts of the locking so to operate that no other lever in the frame can be moved which would allow a train movement conflicting with the train movement controlled by the first lever. The mechanical locking between the levers of the machine also provides for the movement of the levers in proper sequence when the route for a train is being set up, by assuring that the switches must first be properly set and must then be locked in the proper position before the signal governing the route can be cleared.

407. Prevention of switch operation while train is passing. Long bars of steel, called **detector bars**, are held by clips along the outside of the head of the rail at switches. They are of a length greater than the maximum distances between any of the adjacent wheels of a train, and are so mounted that they must move upward above the level of the top of the rail before the switch may be unlocked. They generally are mechanically connected to and operated simultaneously with the lock plungers which pass through holes or notches in the lock rods of switches to lock them in proper position. This method of protection may prove unsatisfactory owing to the increasing width of rail heads, and, especially on electric roads, the relatively narrow wheel treads of which may fail to engage the top of the detector bar while the vehicle is passing over it. Electric track circuits controlling electric locks mounted on the levers of the interlocking machine itself, are becoming quite generally used as a substitute for detector bars in the prevention of switch movement while trains are passing.



Reverse	Locks	Reverse	Locks
1	(2)	13	15-17
2	(14)-19	14	(19)
3	(4)	15	
4	(8) (12)-21	16	(17)
5	(10) (12)-20	17	
6	(16)-23	18	Spare Space
7	Spare Space	19	(14)
8	(9)	20	(12)-(10)
9	11-15-17	21	(12)-(8)
10	(11)	22	(21)
11	15-17	23	(10)
12	(13)-(11)	24	(23)

FIG. 121.—Typical interlocking plan and locking sheet.

408. Arrangement of mechanical interlocking plant. The plan of a single-track line crossing a double-track line is shown in Fig. 121. There is a siding switch on the single line, located so near the double-track line that it is necessary to include it in the interlocking. Derails are shown on all tracks. Those on the double-track, which is assumed to be a steam road, are placed 500 ft. from the crossing, except the "back-up" derails which are about 300

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ft. from the crossing. On the single-track interurban line the derails would be located in accordance with legal requirements or the necessities of the locality. The derail in the siding is placed at fouling distance from the main track. The single switch and each of the derails is locked with a facing-point lock and provided with a detector bar. At the crossing itself a detector bar might also be used to prevent the clearing of signals for a movement on one line while an engine or a detached car was standing on the crossing.

The "home" signals, governing through movement, and the "dwarf" signals, governing reverse movement and the movement from the siding, are located about 50 ft. from the points of the derails. One home signal in the single-track line has two arms: the upper governing the through or high-speed movement, while the lower governs the low-speed diverging movement on to the siding. Distant signals, used to regulate the approach to the home signals, are placed from 1,500 to 4,000 ft. in rear thereof.

The mechanical interlocking machine has a 24-lever frame, the assignment of the various levers being shown in a table. A locking sheet is also given, in which a circle drawn around any lever number indicates it to be in the reversed position. Levers, the numbers of which are not within a circle, are in their normal position.

409. Power interlocking. In mechanical interlocking (Par. 408) the rigidity and mechanical continuity of the connections between any switch, lock, or signal, and the lever that must be thrown in order to move it, is dependent upon to accomplish the desired motion of the unit. It is assumed, in other words, the lever operating a facing-point lock on a switch is moved through its full stroke that the lock is also moved its full stroke. It is further assumed that the movement of the lock lever may be depended upon to release the mechanical locking in the interlocking machine and permit the proper lever to be moved that will clear the desired signal and permit a train to pass over the switch which is locked by the facing-point lock previously mentioned.

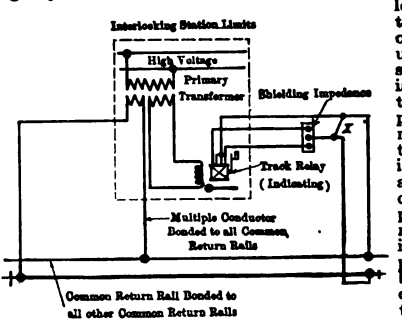


FIG. 122.—Single-rail track circuit at an interlocking plant.

410. Return indication. In power-operated interlocking machines where the only physical connections between the operated units and the levers in the machine consists of insulated conductors which carry small currents, there is no direct assurance, when a switch lever is operated, that the switch itself has moved at all. To insure that it is moved properly and will be locked in a position corresponding to that of the lever, all power interlocking systems provide for what is called a return indication. When the lever in the interlocking machine is moved to cause a switch or signal to be thrown, it cannot at first be moved through its complete stroke nor through sufficient length of stroke to release the mechanical locking between itself and conflicting levers. The lever can only be moved far enough to close the circuit which will cause the desired motion of the switch that is to be operated.

The switch mechanism itself must complete the throwing of the switch, must completely lock it in the proper position, and must then close contacts that will cause current to flow back to the lever in the tower and energize a magnet to release a dog, which has heretofore limited the motion of the lever. After this dog has been released the operator is permitted to complete the stroke of the lever, which will in turn release the mechanical locking between the switch lever and others in the frame, allowing movement of the latter to be made in proper sequence.

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411. The Electro-Pneumatic Interlocking System of the Union Switch and Signal Company. This system is so named because compressed air is employed to shift the switches and signals, while electricity is used to control or direct the admission and discharge of pressure to and from the cylinders by which the shifting is performed. The system is comprised of the following elements: an air compressor (preferably in duplicate for reserve) which, especially in terminal station plants, is often used for many other duties; a main air pipe extending throughout the interlocking system with branch pipes connecting it with each switch and signal to be operated; a double-acting cylinder at each switch which, through a motion plate, operates and mechanically locks the switch in its two positions by movement of the piston; a slide valve for each switch cylinder used to direct the pressure to either side of the piston in order to effect the movement of the latter (Par. 412); a single-acting cylinder, operating the signal (Par. 414); a source of energy (Par. 415).

412. Arrangement and operation of the switch-cylinder slide valve (Par. 411). There are two miniature cylinders employed for shifting the slide valve; two pin valves, operated by electromagnets, control the movement of the pistons in these cylinders. Mounted over the slide valve is a third small cylinder, also under the control of a magnet and pin valve. The piston of this small cylinder engages with and locks the slide-valve against movement save when the magnet is energized and the pin-valve is actuated to permit the pressure to withdraw the lock.

By energizing and de-energizing the magnets in proper sequence, the slide valve is unlocked, shifted, and again locked by the operating and indicating strokes of the lever. During this process each movement of the valve is accompanied by a corresponding unlocking, shifting, and relocking of the switch through the resulting operation of the switch enforced by the piston of its own cylinder. The three magnets are directly connected with contacts that are actuated by one of the levers in the interlocking machine, a separate wire being used for each magnet.

413. Indicating system (Par. 411). In the latest development of this system, a circuit controller is employed which is actuated by each switch movement. When the switch is in one of its extreme positions and locked there, this controller allows a current *of given polarity* to traverse two wires which connect it with a polarised relay in the tower. Conversely, when the switch is moved to and locked in its opposite position, a current of the *reverse polarity* is sent through the relay. During transit of the switch, and, in fact, when the switch is in any position and unlocked, the controller establishes a shunt or short circuit between these two wires. This short circuit renders the apparatus immune, at such times, to the effects of any stray current which might energise the relay. The circuit controller or pole changer, the relay in the tower, and the two wires joining them constitute the fundamental elements of the indication system of this type of power interlocking.

The polarised relay frees one or the other of two electric locks which, previous to this action, has been arresting the *complete* movement of the switch lever in the tower. This incomplete movement of the lever from full "normal" or full "reverse" involves about two-thirds of its total movement. After the partial movement has been made, the *complete* lever movement can be consummated only in the event of one of the two locks which previously restricted the lever's movements becoming energised. The energisation of this lock can occur only when the indicating relay has shifted its armature in response to a reversal of current in the two indicating wires. Such reversal is only possible when the switch has fully moved and become locked in response to the incomplete lever movement. After the lever has been released, its movement may be completed. Following the processes involved in a final execution of the lever stroke, the mechanical interlocking between switch and signal levers permits the shifting of the proper signal lever for train movements over the switch. The current supply to each and every signal leading over the switch is carried through other contacts of the indicating relay, so that unless the relay is energised in the proper polarity and the lever and the switch correspond precisely in position, no signal whatever can be given over that switch. Conversely, should a signal be properly cleared for train movement over a switch, by reason of switch and lever

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corresponding in position, any interference causing a partial or full reversal of either lever or switch would immediately cause the signal to move to the "stop" position. This, the most necessary feature of modern power interlocking practice, gives protection against careless, ignorant, or malicious shifting of a switch by improper means from the position to which it was properly moved by the lever.

414. A single-acting cylinder operates the signal (Par. 411), the signal being held at and returned to the stop position by gravity. Compressed air is admitted to and discharged from this cylinder by means of a pin valve operated by an electromagnet, as in the slide-valve cylinder of the switch mechanism. When energized, this magnet causes the pressure to depress the piston, thereby clearing the signal. When the magnet is de-energized, the air escapes from the cylinder and the signals move to the "stop" position by gravity. Failure of the signal so to move, from any cause, prevents the signal lever from being restored to normal. This incomplete lever stroke prevents the mechanical release of all levers operating switches which lie within the route governed by the signal.

To restore a signal to normal in regular operation the signal lever is moved partly toward normal, where the lock arrests its further movement until the latter becomes energized by the closing of the circuit when the signal assumes the stop position.

415. The source of electric energy (Par. 411) for supplying the current required for the operation of the pin-valves and locks of the system, consists usually of a storage battery of 7 cells in duplicate. This battery has a low ampere-hour capacity and may be charged from any local lighting or power circuit. If direct-current service is obtainable, a resistance is connected in series in order to obtain the desired charging voltage. Charging may be accomplished from an alternating-current line by use of a converter (Sec. 9), a motor-generator set, or a rectifier (Sec. 6). Magnets of 130 ohms resistance will operate pin valves controlling air at from 60 to 100 lb. pressure and are supplied with energy from a 12-volt battery. Two magnets are converted in series. Alternating-current magnets may be substituted for direct-current magnets in the operation of pin valves, and the system operated without batteries. Cylinders of areas and strokes appropriate for the work to be done, are used in various arrangements of switches and frogs. A constant current rate of 5 amp. at 12 volts being sufficient for a large terminal plant.

416. Electric interlocking system of the Union Switch & Signal Co. In this system of interlocking known as the Type "F" the machine for the control of the switches and signals is very similar to that used in the electro-pneumatic system. The switches and signals are driven in this case by electric motors or solenoid magnets working through suitable gears and cams. For the control and indication of a signal, the circuit is similar to that used in connection with the electropneumatic interlocking (Par. 411), except that instead of a magnet actuating a pin valve, there is a relay or other electromagnetic device controlling either an electric motor or a solenoid and suitable holding magnet at the signal. The function of the motor or solenoid is to move the signal arm from the "stop" to the "clear" position. When the arm comes into the "clear" position it is cut out of the circuit automatically, and the holding coil is energized in order to maintain the signal in the clear position so long as the circuit is complete. When the circuit is opened the signal moves to the "stop" position through the action of gravity. The signal-indication circuit is in all respects the same as in electro-pneumatic interlocking.

For the movement of a switch, current is supplied by a stroke of the lever to an electromagnetic controlling device at the switch. Here the controlling device consists essentially of an electrically operated circuit controller so arranged that with the lever in one position the controlling device will establish a circuit to operate the switch motor in one direction; whereas, with the lever in the other position, the connections will be reversed, so that the motor will run in the opposite direction. At the end of the stroke of the switch in either direction, a circuit controller is actuated in such a manner as to cut the motor out of circuit, and partly establish connections for the operation of the switch in the opposite direction when the proper lever movement is subsequently made.

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The switch-indication circuit is in all respects the same as in the electropneumatic system. A polarized relay controlled by a pole-changer at the switch is used. The pole-changer is so arranged that in any position except the extreme ends of stroke, when the switch is locked, the wires feeding the polarized indication relay are short-circuited and disconnected from the source of energy.

Direct-current at a potential of 110 volts is supplied to the switches and signals through heavy mains running from the storage battery in the tower. Current from these mains is fed to the motors through the electrically operated circuit controllers as already explained. These controllers are energized by current from the same battery at the same potential. The resistance of the various pieces of apparatus is such, however, that the current flowing in these control circuits is very small. Consequently the wires from the interlocking-machine levers to the units need never be of larger size than is required for mechanical strength. For the indication circuits, the potential is cut down by resistances, one at each switch or in series with each signal indication circuit, therefore the indication wires may also be small. The selection of signals and their control by the various switches in a route is accomplished through the polarized indication relays and combination contacts in the same manner as in electropneumatic interlocking.

417. The electric-dynamic indication interlocking system of the General Railway Signal Co. (see Par. 418 to 420). The source of power consists of a storage battery with its charging unit, which furnishes current at 110 volts for the operation of the switch and signal motors. Power-control apparatus is introduced between the battery and the interlocking machine. The interlocking machine proper is provided with levers, of the sliding type, built generally in units so that any lever with its safety and indication magnets, accessories and housing may be removed from the frame without disturbing adjacent levers. The mechanical locking is of the vertical type, the tappet bars being moved vertically by the horizontal motion of the levers through the medium of a cam slot in each lever. Fig. 123 shows a cross-section of a unit-lever type electric interlocking machine, and Fig. 124 shows typical circuits for this interlocking system.

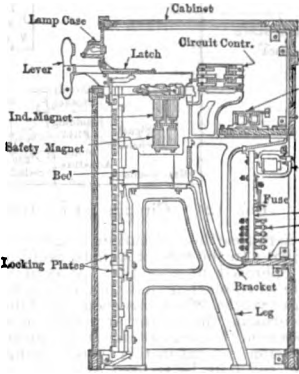


FIG. 123.—Electric interlocking machine.

Alternate levers have their handles turned upward and downward. Beside the interlocking machine, the system comprises the switch and signal mechanisms with their operating and indicating circuits and means for the prevention of unauthorised movement of any unit. Each switch or derail is thrown and locked by a switch and lock movement driven by a series-wound direct-current motor. Two wires are used for this control, one for the normal and the other for the reverse operation. These same wires are used for indicating purposes, the normal control wire being used for the reverse indication and the reverse control wire for the normal indication. The circuit is connected to the main common-return wire at each switch.

The control circuit for each switch and signal is broken through the proper track and line relay contacts, also through the proper lever, switch and signal circuit controller contacts, so as to insure that conditions are safe and proper for the movement of the respective switch or signal. In small plants the breaking or selecting of the control circuits is done at each unit; in large plants it is usually the practice to do all selecting of circuits at the control station, by means of repeater relays, which affords greater simplicity and a minimum amount of wire.

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418. Indication locking (Par. 417). The distinctive feature of the elec tric-dynamic system is in its method of "indication locking," which is of th so-called dynamic type, in that the source of energy used to supply curren for the operation of the switches and signals is *not* used to supply curren for energising the indication magnets in the interlocking machine. I this system, whenever a switch has completed its movement and has bee locked through the operation of the motor which drives it, the completion its operation disconnects the motor from its load, permitting the former operate as a generator under the momentum which has been acquired by t armature in operating the switch and lock. The current generated by th motor acting as a generator, is transmitted back to the interlocking machi

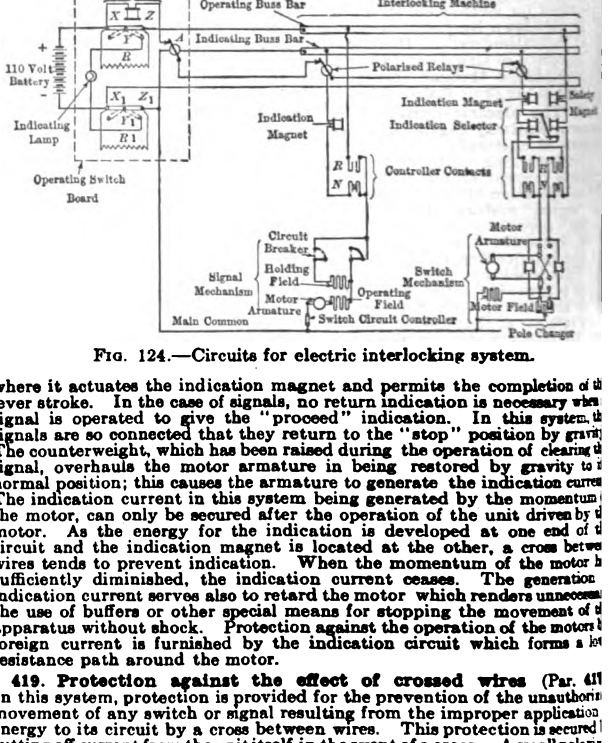


FIG. 124.—Circuits for electric interlocking system.

where it actuates the indication magnet and permits the completion of th lever stroke. In the case of signals, no return indication is necessary when signal is operated to give the "proceed" indication. In this system, th signals are so connected that they return to the "stop" position by gravit The counterweight, which has been raised during the operation of clearing th signal, overhauls the motor armature in being restored by gravity to i normal position; this causes the armature to generate the indication curren The indication current in this system being generated by the momentum the motor, can only be secured after the operation of the unit driven by th motor. As the energy for the indication is developed at one end of th circuit and the indication magnet is located at the other, a cross betwe wires tends to prevent indication. When the momentum of the motor h sufficiently diminished, the indication current ceases. The generation indication current serves also to retard the motor which renders unnecessa the use of buffers or other special means for stopping the movement of th apparatus without shock. Protection against the operation of the motors b foreign current is furnished by the indication circuit which forms a lo resistance path around the motor.

419. Protection against the effect of crossed wires (Par. 41 In this system, protection is provided for the prevention of the unauthoriz movement of any switch or signal resulting from the improper application energy to its circuit by a cross between wires. This protection is secured cutting off current from the unit itself in the event of a cross. A small polariz relay is connected in each switch or signal circuit through which all operati and indicating currents must pass in such a direction as to maintain the rel contact closed. Conversely, currents from unauthorized sources such crosses are compelled to pass in the opposite direction, thus opening polarised relay. All these relay contacts are in series and control the circ of the retaining magnet of a circuit breaker on the operating switchboa

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This circuit breaker controls the supply of current from the storage-battery to the interlocking machine. A check on the integrity of the cross-protection system is secured by having all necessary contacts and connections either on closed circuit or used in each process of operation and indication so that failure of any individual member would prevent operation and indication and would be promptly detected. A necessary feature in this system as in other electric interlockings, is the prevention of indication current from reaching any lever, while the unit normally under the control of that lever is being operated due to crossed wires from other units which may be indicating at the moment. This protection is secured by means of a safety magnet located below the indication magnet on each lever, Fig. 123. The windings of this safety magnet are included in the operating circuit of the lever, and its magnetic properties are so proportioned to those of the indication magnet, that if both were energised at the same instant, the safety magnet would overpower the indication magnet and prevent the latter from lifting its armature to trip the indication latch in the lever. Normally, the armature of the indication magnet rests upon the poles of the safety magnet. As a further safeguard, an indication selector is provided with its magnet coils in series with the safety magnet and in the control circuit. The function of this selector is to prevent possible receipt of an improper indication during the interval between the time that a lever is moved to the opposite position from that which it previously occupied, and the time the movement of the switch mechanism itself is complete.

420. Operation in reverse direction (Par. 417). The last portion of the stroke of the locking plunger at the switch mechanism operates the pole-changer which cuts off the operating current and puts the circuits into action for an operation in the opposite direction. The breaking of this circuit de-energises the safety magnet. permitting the indication magnet to be energised by the current generated in the revolving motor armature. The operating circuits are so designed that the magnetic control of the pole-changer insures a correspondence in position between the lever in the machine and the operated unit outside.

THE BLOCK SYSTEM

421. Classification of block signaling systems. The block system provides for the division of the railroad into lengths of track of defined limits, over which railway traffic is controlled by block signals. Block signals and block-signaling systems may be classified as follows: a (Par. **422**), manual, in which the signals are operated by hand on orders or information received by telegraph or telephone; b (Par. **423**), controlled manual, in which some means (generally electrical) are employed to necessitate the cooperation of the signalmen at both ends of a block in order to clear the signal admitting a train on the block; c (Par. **424**), automatic, in which the signals are power-operated and are controlled by the trains themselves through the action of their wheels upon electric circuits constituted by the rails of the track. Such signals indicate the presence of a train or single car or engine in the block and also such conditions as the presence of a broken rail, an open switch or a car standing upon a siding within fouling distance of the main track.

422. In the manual block system, when a train has passed into any block, the signalman sets his signal to the "stop" position behind it, and notifies the signalman at the entrance to the next block of the approach of the train. This second signalman in turn consults his record to see if the signalman controlling the entrance of the third block has reported the passing of all trains out of the second into the third block which previously have been admitted to the second block. If such is the case, the signalman at the entrance of the second block will set his signal to indicate "proceed" and permit the approaching train to enter the second block. Such a system necessitates the use of very carefully prepared rules and is dependent for its safe and successful performance entirely upon the watchfulness of the signalmen and the precision with which they perform the duties prescribed for them by the rules. On single-track railroads, this system necessarily involves the protection of trains against opposing movements, and is in general supplemented by the issuance of train orders from the despatcher, which provide for the meeting of trains at other times or stations than those specified in the time-table.

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423. In the controlled-manual block system, the levers by which the signals are operated are provided with electric locks. The solenoids of these locks must be energized to release the levers before the signals may be cleared for the passage of trains. Circuit controllers, called "block instruments," are placed in each block station and are so interconnected electrically as to require that a definite sequence of operations be performed by the signalmen at both ends of each block before the signal at the entrance of a block may be cleared. Signal bells and keys are provided for the transmission of code signals between adjacent signal stations. Adjuncts such as indicators and electric track circuits may also be installed, whereby the presence of a train in the block may effect the electric locks in such manner as to insure its own protection. The variety of apparatus and circuits necessary to afford varying degrees of protection are too diverse to be herein enumerated.

424. The automatic block system, which is continually coming into more extended use, has its foundation in the electric track circuit. Its cost of construction and maintenance is relatively high. Its operating cost is low as compared with any system requiring the constant presence of signalmen on duty, as would be necessary with manual or controlled-manual systems. The principles of the electric track circuit are considered at some length in Par. **392** to **403** incl.

Seldom can automatic block signals be controlled by track circuits alone. Such conditions as the existence of a number of track circuits in one block and where the position of one signal arm must be made to determine the position of another, require the use of line-wire circuits, each of which is provided with its own source of energy and one or more relays for direct control of the local signal circuits themselves. These line circuits include contacts carried on the armatures of the track-circuit relays; the latter thus indirectly control the signals through the medium of the line circuits.

The line circuits frequently pass through circuit controllers actuated by the switches in the tracks, so that the opening of any switch in the block will directly open the signal line circuit. Line circuits for the control of signals are always so designed that the source of energy is located at one extreme end of the circuit and the relay at the other extreme end of the circuit, any controlling devices are being located between these extremes. This is important in order to prevent the possibility of false "clear" indications from the supply of energy to the line relay in case crosses or grounds occur on the circuit.

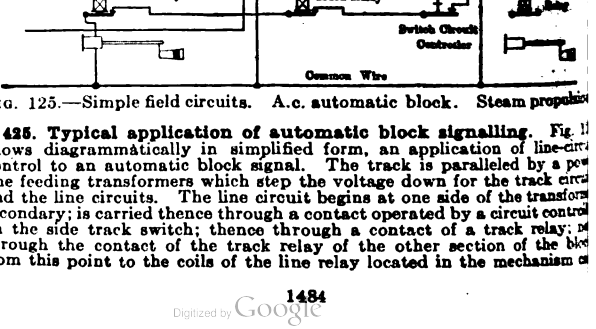


FIG. 125.—Simple field circuits. A.c. automatic block. Steam propulsion.

425. Typical application of automatic block signalling. Fig. 1 shows diagrammatically in simplified form, an application of line-circuit control to an automatic block signal. The track is paralleled by a power line feeding transformers which step the voltage down for the track circuit and the line circuits. The line circuit begins at one side of the transformer secondary; is carried thence through a contact operated by a circuit controller on the side track switch; thence through a contact of a track relay; thence through the contact of the track relay of the other section of the block from this point to the coils of the line relay located in the mechanism of

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of the signal; and thence back over a common wire to the other side of the transformer secondary.

Fig. 125 also indicates how a portion of one of the track rails on the siding is insulated from adjacent rails and bonded to the opposite main track rail. If a train or car on the siding moves to within fouling distance of the main track, it will thus shunt the relay of the track section in which the switch is located.

426. Automatic block signalling applied to electric railways. Fig. 126 shows a simplified form of automatic block signal circuit for one track of a double-track railway using direct-current propulsion and two-rail alternating-current track circuits, the signals themselves being operated by direct current from batteries. Alternating-current track relays are generally of the vane, galvanometer or induction-motor type. In the first named, an aluminum sector revolves between the poles of a C-shaped laminated core, in which the winding is placed. This winding is connected across the rails of the track circuit and receives current through the rails from the transformer

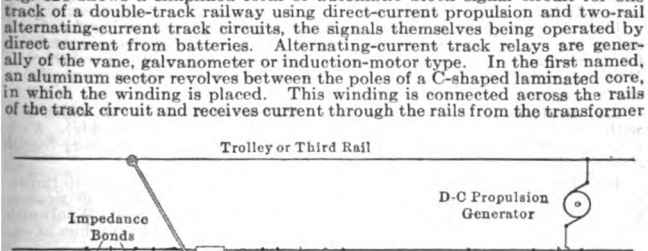


FIG. 126.—Typical circuits. Power supply for a.c. track circuits.

at the other end of the track circuit. The galvanometer type of relay has a set of fixed coils energized from a local source, and a movable coil energized from the track circuit. In the induction-motor type of relay both the track and the local windings are fixed, and the rotor is made to revolve by phase displacement in the current of the two windings. In all types the moving member carries or actuates contacts through which are controlled the circuits controlling the operation of the signals themselves.

The transformers which supply energy to the track circuit also supply energy to the local windings of motor-type track relays together with any line or secondary relays necessary in the circuits; in addition they supply energy for the operation of the signal mechanisms proper. The transformer secondary windings supplying current to the track rails are generally provided with a number of taps, so that the voltage impressed on the track may be regulated to suit the length or characteristics of the track circuit. The secondaries are naturally provided with series resistances which limit the current output when the secondary is short-circuited by the presence of a car in the block.

BIBLIOGRAPHY—RAILWAY SIGNALING

427. Association reports. Comparatively few books have been written on the subject of railway signaling, most of the available data being found in periodical technical literature, in publications of engineering societies, and in the bulletins and catalogues issued by the manufacturers of signal apparatus. The last mentioned source is voluminous, as such publications are frequently issued and contain much valuable technical information.

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The following associations regularly publish committee reports on signaling. Publications are listed below their names as follows:

American Electric Railway Association, 29 West 39th St., New York, N. Y. Proceedings, Standard Rules.

American Railway Engineering Association, 900 So. Michigan Ave., Chicago, Ill. Bulletins, Manual of Approved Practice. (This applies mostly to steam railroad signaling.)

American Railroad Association, Signal Division, 75 Church St., New York, N. Y. Journal (Quarterly), Manual (Standard plans and specifications), Index to Signal Literature.

The rule book of the American Railroad Association, containing the standard code of train rules, block-signal rules and interlocking rules, is the basis from which almost all other rule books have been developed. The School of Railway Signaling, Utica, N. Y., publishes text books and correspondence courses of study in railway signaling.

428. Periodicals. The following are the principal periodicals which deal with signaling: *Electric Railway Journal*, 239 West 39th St. (weekly). *Railway Age*, Woolworth Bldg., New York, N. Y. (weekly). *Railway Signal Engineer*, Transportation Bldg., Chicago, Ill. (monthly).

429. Dictionaries and published bibliographies. The most important compilation of information on signaling is the signal dictionary, second edition, 1911, *Railway Age Gazette* (now *Railway Age*), Woolworth Building, New York, N. Y. By far the most complete bibliographies of signaling are the following:

Index to Signal Literature, Vol. I, October, 1910, Railway Signal Association, Bethlehem, Pa. (now American Railway Association, Signal Section, 75 Church St., New York, N. Y.).

Bibliography on Block Signals for Electric Railways, pages 227 to 298 Proceedings of the American Electric Railway Association, 1913.

ELECTROLYSIS OF UNDERGROUND STRUCTURES

BY ALBERT F. GANZ

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REVISED BY ALBERT S. RICHEY

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NATURE AND CAUSES

430. General cause of electrolysis. Electrolysis is defined as chemical decomposition by an electric current. If the anode by which an electric current enters an electrolyte consists of a metal which can combine chemically with the anions set free by the electrolytic action, then this anode will be decomposed or corroded. This electrolytic corrosion of an anode is what will be referred to as electrolysis in this discussion.

431. Stray or vagabond currents. Stray or vagabond currents are electric currents which have leaked from grounded electrical distributing systems and flow through earth. These stray currents in their path through earth may reach underground metallic structures, such as piping systems and the lead sheathing of cable systems.

432. Stray currents from direct-current electric railways. In the simplest arrangement of electric railways using the tracks as return conductors, the rails are connected to the negative terminal of the generator at the power station or substation, and the current returns to the station through the rails. Where these rails are in contact with ground, part of this current will shunt through the earth and through underground metallic structures, as is illustrated in Fig. 127. Current will leave the rails and enter the earth at distant points, and will return to the rails in the neighborhood of the power station or negative feeder taps.

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433. Electrical properties of soil. Soil when dry has such a high resistivity that, practically, it does not conduct electric current. Under ordinary conditions, however, soils contain considerable water with various salts in solution, making them electrolytic conductors. An electric current therefore passes through soil by electrolytic conduction. The resistivity of soils varies within very wide limits, depending upon the amount of moisture and salts present. Most values lie between 300 and 30,000 ohms per centimeter cube, with the average soil within the more narrow limits of 1,000 to 5,000 ohms per centimeter cube.

434. Distribution of potentials in rails and earth. For the simple arrangement illustrated in Fig. 127, the distribution of potentials is shown in Fig. 128. The following assumptions are made in the development of these curves: (a) the negative bus bar is connected to the rails at the power station by an insulated cable, with no other ground connections; (b) the line extends in one direction only; (c) the load is uniformly distributed over the line; (d) a pipe of uniform resistance lies in the earth parallel to these rails (e) the resistance between the rails and pipe is everywhere the same. With these assumptions, the current in the rails will increase uniformly from zero at the end of the line to its greatest or total load value at the power station O. Taking the negative bus bar and this point O as the datum or zero of potential, the potential of the rails is represented by the parabola OI. The voltage OD is the total rail drop. There will be a neutral point N in the rails at a distance 0.42 of the total length of the line from the power station where these rails are at the ground potential. Between the power station and N, the rails are negative with respect to ground, and current tends to flow from ground to the rails; while from N to the end of the line E, the rails are positive with respect to ground, and current tends to flow from the rails to the ground.

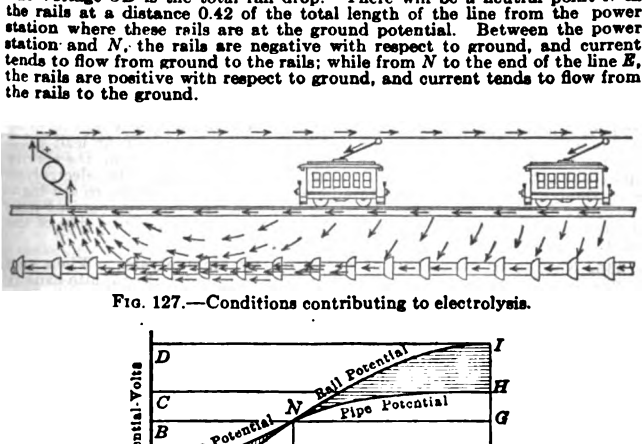


FIG. 127.—Conditions contributing to electrolysis.

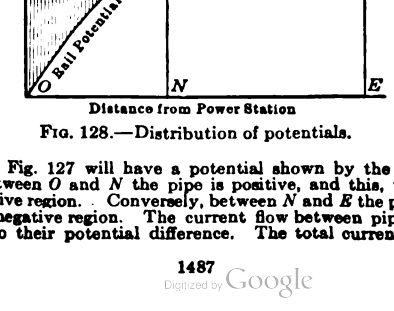


FIG. 128.—Distribution of potentials.

The pipe of Fig. 127 will have a potential shown by the curve A-H in Fig. 128. Between O and N the pipe is positive, and this, therefore, constitutes a positive region. Conversely, between N and E the pipe is negative and this is a negative region. The current flow between pipe and rails is proportional to their potential difference. The total current flowing from

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rails to pipe, shown by the shaded area *N-I-H*, is equal to the total current flowing from pipe to rails, shown by the shaded area *O-A-N*. The current on the pipe will be a maximum at the neutral point *N*, and will be zero at the power station and at the end of the line. The greatest negative potential *C-D* of the pipe, with reference to the rails, will be at the end of the line; and the greatest positive potential *O-A* of the pipe will be at the power station. For the case assumed, the greatest positive potential will be twice the greatest negative potential. The total rail drop *O-D* is equal to the sum of the three voltages, the greatest positive pipe potential *O-A*, the greatest negative pipe potential *C-D*, and the voltage drop on the pipe *A-C*. This voltage drop on the pipe is a measure of the current flowing on it, and is therefore a measure of the danger from electrolysis to which the pipe is subjected. If no current flows on the pipe there will be no voltage drop on it, and the pipe potential curve *A-N-H* will coincide with the horizontal line *B-G*. The positive and negative potentials of the pipe referred to the rails will however be increased, which shows quite clearly that the magnitude of the voltage between pipe and rails is not a measure of the danger from electrolysis.

Where there are rail networks and underground piping networks, the potential distribution curves are correspondingly altered, but follow the general trend of those given in Fig. 128.

435. Where electrolysis occurs. Wherever electric current leaves a metal to flow to soil, corrosion from electrolysis is produced. In positive regions stray currents generally flow from underground structures and corrode these structures by electrolysis. The greatest density of current leaving will generally occur where the positive potential is highest, namely, in the neighborhood of the power station; here the destruction by electrolysis is usually most severe. Underground structures may also be damaged by electrolysis in regions where they are negative to the rails, and far away from any return feeder connections, because of currents shunting from one set of underground conductors to an adjacent set. A case frequently met in practice is where underground gas or water service pipes cross near lead cable sheaths to which they are positive, and where current flows from the service pipes through soil to the cable sheaths, damaging the pipes by electrolysis even though they are negative to adjacent trolley rails. If there are high-resistance joints in a pipe line carrying stray electric current, current may shunt around these joints and produce corrosion on the positive side of the joint.

436. Nature of corrosion of cast iron by electrolysis. When cast iron is corroded by electrolysis, the oxides of iron mixed with graphite usually remain in place, leaving the outward appearance of the pipe unchanged. This material resulting from electrolysis of cast iron usually has the consistency of hard graphite and possesses little mechanical strength. The oxide of iron together with the surrounding soil frequently prevent noticeable leakage of gas or water, even when corrosion has extended entirely through the metal of the pipe. In such cases a physical examination with a test hammer is required to establish definitely whether the pipe has been damaged by electrolysis. Current generally leaves iron pipes for soil from localised areas, resulting in localized corrosion of the metal. In the case of cast iron corroded by electrolysis, the graphitic residue usually can be dug out with a knife, exposing pits in the pipe.

437. Nature of corrosion of wrought iron and steel by electrolysis. Where electric current leaves a wrought-iron or steel pipe for soil, the oxide of iron resulting from electrolysis is diffused through the soil. The action is also generally localised, resulting in pits which eventually may go entirely through the wall of the pipe.

438. Relative danger from electrolysis to cast-iron and wrought-iron or steel pipes. For a given current leaving an iron pipe for soil, there is practically no difference in the rate of corrosion by electrolysis among cast iron, wrought iron and steel. The electrical resistivity of cast iron is, however, about ten times as great as that of wrought iron or steel, and the usual lead joints in cast-iron pipes have a resistance which is many times greater than the screw-coupling joints usual with wrought-iron and steel pipes. For these reasons a given voltage drop through earth will, in general, cause a much smaller current to flow on a cast-iron pipe than on a wrought-iron or steel pipe, thus practically making cast-iron pipes much less

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subject to electrolysis than wrought-iron or steel pipes with screw-coupling joints. With ordinary conditions of soil, and with current densities of less than 5 amp. per sq. ft. (about 5 milliamperes per sq. cm.), as ordinarily found with stray railway currents leaving underground piping for surrounding soil, iron is oxidised by electrolysis at the rate of approximately 20 lb. (9 kg.) per year for every ampere leaving the pipe. Under some conditions, particularly with very small current densities, the corrosion may be as much as 40 per cent. greater, although usually not to exceed 10 per cent. greater than the theoretical rate, while with larger current densities than the above the corrosion may be as low as 20 per cent. of the theoretical rate. The amount of corrosion produced by electrolysis is independent of the applied voltage, except in so far as this voltage determines the amount of current flowing.

439. Corrosion of lead and tin. Where electric current leaves lead or lead alloyed with a small percentage of tin to flow to surrounding soil, the metal is oxidised by the electrolytic action, forming white or yellow salts. The theoretical rate of oxidation of lead by electrolysis is approximately 74 lb. (34 kg.) for every ampere leaving the lead in one year. The actual may vary from the theoretical rate, as in the case of iron. Where lead-sheathed cables are drawn in clay conduits, stray current may flow from the cable sheaths to water in the conduit or to the damp conduit itself. In such cases pittings are usually produced at the lower surfaces of the cable sheaths. Owing to the thin walls usual with lead cable sheaths, together with the high electrochemical equivalent of lead, such cable sheaths are damaged by electrolysis far more easily than are iron pipes.

ELECTROLYSIS SURVEYS

440. Nature of survey. The principal measurements generally made in an electrolysis survey of an underground pipe or cable system are as follows: a, voltage measurements between the pipes or cable sheaths and the rails (Par. **441**); b, voltage measurements between the pipes or cable sheaths and other underground metallic structures (Par. **441**); c, measurements of current flowing on the pipes or cable sheaths (Par. **442**). In order to be able to completely judge the electrolytic condition of an underground metallic system and to be able to decide upon remedial measures, it is necessary in addition to make measurements of rail drop and of the resistivity of the soil in various parts of the system.

441. Potential survey. To make a potential survey, potential differences between the underground structures and rails are measured at a number of points along every street where these structures and electric railway tracks are located. With lead cable sheaths contact is made directly on these sheaths in manholes. With underground pipes contact may be made by means of service pipes, hydrants or drip connections. The connections used for the potential measurements may be tested for continuity by means of an ammeter momentarily connected between the contacts with a dry cell in series if necessary. Where there are a number of underground metallic structures which may be affected by electrolysis, it is desirable to make simultaneous measurements of potential difference between the rails and each of these structures, and from these results to compute the potential differences between each pair of structures.

442. Current survey. To determine the current on a pipe or cable sheath, the drop between two points on a continuous length of pipe or sheath is measured by means of a millivoltmeter. From tables of pipe and cable sheath resistances, the strength of current may be computed by Ohm's law. Where reasonable accuracy is required, the resistance of a pipe or cable sheath should be measured instead of computed from its dimensions. In the case of lead cable sheaths, the drop measurements usually can be made in manholes where the cables are exposed. In the case of iron pipes, the millivoltmeter leads must be connected directly to the metal of the pipe on which current is to be measured; and no joint must be included between the two contacts. Service pipe connections cannot be used for such current determinations. Temporary contacts are conveniently made by means of a sharpened piece of steel rod, fastened in a wooden handle, with connecting leads soldered to the rod inside of the handle. For permanent connections which can be used at any time for measuring drop on the pipe without ag-

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exposing the pipe, rubber-insulated wires may be soldered to brass plugs and these screwed into the pipe; the wires are then brought to the street surface, preferably inside of the curb, and the free ends left in drip or service boxes. It should be noted that small potential differences, such as 0.1 millivolt or less, may be caused by local galvanic or thermal action, and care should therefore be taken that such observations do not lead to erroneous conclusions.

Current measurements on pipes or cable sheaths frequently are made at two or more stations simultaneously in order to determine whether there is a gain or a loss of current between the stations. This is the most reliable method of determining localities where current is leaving the structure and where corrosion may be taking place.

443. Instruments. Millivoltmeters for measuring drop on pipes or cable sheaths should have as low a millivolt range and as high a resistance as practicable. Moving-coil permanent-magnet instruments of the Weston type having zero in the centre of the scale are the most suitable for this work. The millivoltmeter can be conveniently combined in one instrument with a voltmeter for the potential measurements. These instruments may be obtained with resistances of 600 ohms per volt and even higher where necessary. Convenient ranges for such a combination instrument are 5, 50 and 500 millivolts, and 5 and 50 volts. Ordinary shunts adjusted for 50 millivolts drop can also be used with this instrument. Convenient ranges for such shunts are 5, 50 and 500 amperes. Recording instruments having the same ranges as above noted can also be used for obtaining 24-hr. records, by means of which the characteristic variations of a potential difference or of a current may be obtained. Such recording instruments with 1-hr. clocks are useful also for recording potential differences and current in cases where, due to infrequent service, it is necessary to take readings for periods of from ½ hr. to 1 hr.

444. Measurement of earth potential. It is possible to trace the path of stray current through earth by measuring potential differences between points in the earth. When iron rods are used as electrodes for making contact with earth an error may be introduced, where the voltage measured is small, due to a possible difference in the polarisation voltages at the two electrodes. This polarisation voltage may be eliminated by using a non-polarisable electrode, developed by Dr. Haber. With this electrode electrolytic contact is made with soil by means of a zinc sulphate solution contained in a porous cup; the potential lead is connected to a zinc rod dipping in the solution. With this electrode the contact resistance is very high, so that a zero method and not an indicating voltmeter should be used for the potential measurement. This makes the method very troublesome for ordinary electrolysis testing, where the voltages to be measured generally fluctuate constantly. For this reason this electrode is useful only in very special cases. For description of the non-polarisable electrode see the paper by Haber and Goldschmidt listed in the bibliography.

445. Measurement of earth current. It is often desirable also to measure directly the flow of stray current through earth. This can be done by means of the Haber earth ammeter, which consists of a wooden frame supporting two copper sheets insulated from each other by a plate of mica or glass. Insulated copper wires connect the two copper sheets with an ammeter. To use the frame, the two copper plates are coated with a paste made of copper sulphate and a 20 per cent. sulphuric-acid solution for the purpose of equalising polarization voltages. A wetted piece of parchment paper is then laid over the paste, and the remainder of the frame is filled with soil. If the frame be buried in the earth with its plane normal to the direction of the current flow, the ammeter will indicate the current which is intercepted by the buried frame. This earth ammeter is well suited for measuring current flow between a pipe and earth. For this purpose the frame is buried in the earth near and parallel to the pipe. By using a recording instrument in connection with the earth ammeter, the characteristic variations of the current leaving a pipe can also be determined, and in this way the identity of the current can often be established. For description of the earth ammeter see the paper by Haber and Goldschmidt listed in the bibliography.

446. Physical examination. From a study of the results of a general electrolysis survey, it is possible to determine in what regions current is

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leaving an underground system. Excavations then may be made where current is leaving, and the exposed structures may be tested with a hammer for effects of electrolytic corrosion.

PREVENTION OF ELECTROLYSIS

447. General description of different methods. The methods which have been used to minimise electrolysis from stray railway currents may be divided into three classes: a, the **insulation method** (Par. **450** to **452**), which is intended to increase the resistance of the path of the current through earth; b, the **drainage method** (Par. **453** to **455**), which removes the current from structures by metallic connections or bonds between these structures and the railway return circuit; and c, the **return-feeder method** (Par. **456** to **458**) which reduces the voltage drop in the grounded rails.

448. Brief description of double-trolley systems and where used. Double-trolley railways may be provided with positive and negative overhead trolley wires as used for example in Cincinnati and Havana; with positive and negative conductors in underground conduits, as used on the surface lines on Manhattan Island and in Washington, D. C.; or with separate insulated third and fourth rails for the positive and negative conductors, is used on the Metropolitan District Railway in London. Where both sides if such circuits are insulated from ground, there can be no stray earth currents and no electrolysis.

449. Objections to double-trolley systems. The principal objection to the underground double-trolley system is the very high cost of installation, which makes this method practicable only in densely populated districts. The principal objections to the double-overhead-trolley system are the high cost of installation and the complication resulting from two overhead trolley wires, especially at crossings and where several lines meet and are on common tracks.

450. Insulation of rails. Where a road operates on a private right-of-way, the rails can be practically insulated from ground, and the escape of current from the rails substantially prevented. For surface or subway lines this can be accomplished by placing the rails on wooden ties above ground and using broken stone for ballast. For lines operating on elevated structures substantial insulation may be secured by fastening the rails on wooden ties and keeping them out of metallic contact with the structure.

The leakage resistance of street railway road beds varies greatly with the construction. Tests by the Bureau of Standards indicate resistances per 1,000 ft. of track, as follows:

Solid concrete ballast and non-porous pavement, 0.2 to 0.5 ohm for single track, or 0.15 to 0.35 ohm for double track; clean crushed stone foundation under a concrete paving base, 0.6 to 1.5 ohms for single track, or 0.4 to 1.0 ohm for double track; full crushed stone ballast, with tarvia finish, 2 to 5 ohms; ties embedded in earth road bed, 1 to 1.5 ohms; open construction, 10 to 15 ohms in very dry weather, dropping to 3 to 5 ohms when wet; except where specified, the above figures are for single track, and unless otherwise stated, the resistance of double track is practically one-half that of single track.

Zinc chloride and other chemical salts, used as preservatives, render ties highly conductive, and greatly increase leakage currents. Creosote has very little effect on the resistance of wood ties, but a treating material consisting of 75 per cent. gas oil and 25 per cent. creosote appears to increase their resistance materially.

451. Insulation of pipes. Attempts have been made to insulate pipes from earth by paints, dips and insulating coverings. It is doubtful whether there is any instance on record where damage by electrolysis has been effectually prevented in this way if the voltage conditions were at all severe. On the contrary, there have been cases where efforts to prevent electrolysis of pipes by this means have undoubtedly done actual harm. In general, this may be said to be due to peculiarities of the coatings used, which cause them to fail in spots and thus allow greatly aggravated cases of local damage to occur, in place of the more distributed trouble which would take place if the pipes were not coated, assuming the voltage conditions to be the same in both cases. Coatings of the thickness commonly used for covering service

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pipes and similar structures can hardly be expected to last more than a few years, their useful life probably not exceeding a year in the majority of cases. A careful study of the conditions under which the failure of insulating coatings under electric stress takes place shows that it is due to the combined action of the moisture and electric stress. The manner in which these coatings usually fail under electric stress shows that they may under certain circumstances increase the trouble from electrolysis. Breaking down as they do at isolated points, the discharge of current from the pipes is concentrated at those points and the pitting is likely to be more serious than if the coating were not used at all.

452. Insulating joints in pipes or cable sheaths. Current flow on pipes or cable sheaths can be practically prevented by using a sufficient number of insulating joints. A pipe line laid entirely with insulating joints, or uniformly high-resistance joints, has such a high resistance that it is practically free from electrolytic danger. It is sometimes possible to use comparatively few insulating joints to break up the electrical continuity of a pipe line, and so to protect the line from electrolysis. Such joints, however, must be installed only after careful tests have shown that the current is not likely to shunt through earth around them and thus produce a condition worse than the previous one. This effect depends largely upon the potential gradient through earth, and also upon the electrical resistivity of the soil. In general, the drop across an insulating joint in a cast-iron main should not exceed 0.1 to 0.4 volt, while in wrought iron pipes the drop should not exceed one-third of these values; in either case the lower limit applies to joints located in low, wet places, and having short-leakage paths.

For wrought-iron or steel pipes of small size, the Macallen, the Hammon and the Dresser insulating joints are largely used. For large sizes, a flanged insulating joint as shown in Fig. 129 is often used. For gas or oil pipes, red fibre has been found a satisfactory insulating material, while for water pipes,

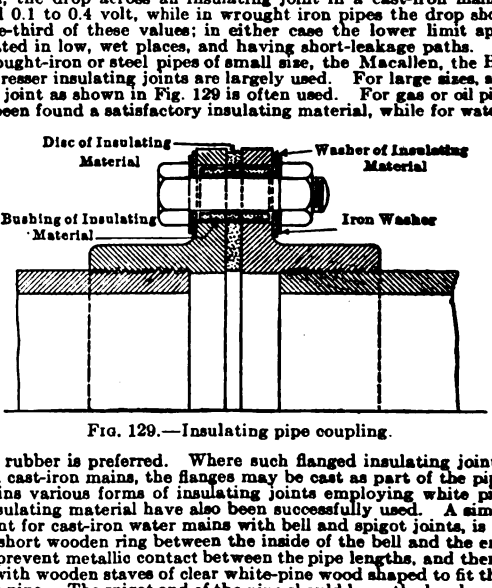


FIG. 129.—Insulating pipe coupling.

soft sheet rubber is preferred. Where such flanged insulating joints are to be used in cast-iron mains, the flanges may be cast as part of the pipe. For water mains various forms of insulating joints employing white pine wood for the insulating material have also been successfully used. A simple form of this joint for cast-iron water mains with bell and spigot joints, is made by placing a short wooden ring between the inside of the bell and the end of the spigot to prevent metallic contact between the pipe lengths, and then calking the joint with wooden staves of clear white-pine wood shaped to fit the curvature of the pipe. The spigot end of the pipe should have the bead removed or be cast without a bead. Any leaks that develop are stopped with white-pine wedges. These joints have been found satisfactory for pressures up to about 75 lb. per sq. in. (5.27 kg. per sq. cm.). Higher pressures sometimes cause moderate leakage through the pores of the wood; this has been overcome by dipping the inner ends of the staves in red lead. The staves may also be reinforced by an iron band clamped around the spigot end of the pipe. Cement joints in cast-iron pipes as ordinarily made do not produce metallic

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connection between the adjoining pipes and may practically be classed with insulating joints. Metallic contact may be positively prevented by inserting a ring of any cheap insulating material between the end of the spigot and the interior of the bell.

453. Drainage method. Since stray currents cause damage only where they leave metallic structures and flow to surrounding soil, the current may be removed by connecting or bonding these structures, by metallic conductors, to the rails or to the negative return circuit or directly to the negative bus bar. This is known as the drainage method. The lead sheaths of underground cables form continuous and uniform metallic conductors, and it is possible to protect such cable sheaths against electrolysis by bonding them to the railway return circuit. Through such bond connections however only enough current should be drained from the cable sheaths to render them at the same potential or slightly negative with respect to neighboring structures. The effectiveness of drainage as a protective measure depends upon the uniformity of the conductor to be protected. The method is therefore not generally applicable to underground piping systems, because these do not form continuous electrical conductors, but are more or less discontinuous networks. While lead-calked joints usually have a relatively low resistance, they may develop such high resistances as to make trouble as noted below.

454. Possible dangers from drainage connections. Drainage connections considerably reduce the resistance of the path of stray currents, thereby increasing the total amount of stray current through earth and on underground structures. The danger of local electrolysis damage due to the shunting of current around high resistance joints is thereby increased. Further, unless all underground metallic structures are bonded together in such a way that where different structures come into proximity, all are maintained at the same potential, damage may result from a flow of current through the earth from one such structure to another. Also, where, for instance, drainage is applied to water mains and not to parallel gas mains, relatively large stray currents may flow through buildings by way of the service pipes where such pipes are in metallic contact, such as through water heaters; accidental contact between such service pipes within buildings may also cause arcing, with possible danger from gas leakage or fire.

Drainage connections to underground structures, therefore, should be used with caution, and in general designed so that only small amounts of stray currents will flow over such connections. Drainage connections to underground cable sheaths are generally necessary to protect the lead covering against electrolysis. In the case of pipe systems, however, such drainage connections should not be used except in special cases, such as a final measure to remove relatively small currents.

455. Reverse-current switches for drainage connections. Cases arise where the polarity of underground structures reverses at times with reference to the railway return circuit. Consequently, where these structures are provided with metallic connection to the railway return circuit, current would be made to flow to these structures when these are negative in potential. To prevent this, automatic reverse-current switches may be used in series with such drainage connections. The action of these switches is to keep this circuit open while the structures are of negative potential, and closed while they are of positive potential. Such reverse-current switches are frequently used in connection with drainage connections from telephone cables.

456. Insulated return feeder system. Since the drop in potential in grounded rails is the cause of the flow of stray current through the earth, stray currents will be reduced in the proportion that the drop in the rails is reduced. It is therefore desirable to use heavy rails of high electrical conductivity, and to maintain these rails well bonded, so that they form continuous low-resistance conductors. The next important consideration is to limit the distance from the supply station to which it delivers direct-current power, so that current is not returned through an excessive length of track; this may be accomplished by the use of a number of distributed substations. Finally, the current may be removed from the rails by means of insulated return feeders connected to the rails. These feeders draw current from the rail at such points as are necessary to avoid an excessive potential gradient

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in the tracks and an excessive total voltage drop in the tracks. Where it is necessary to bring current back from a distant point in the tracks, it is sometimes more economical to employ a negative booster in series with a return feeder of small cross-section than to make this feeder of cross-section large enough to drain the required current from the tracks at the distant point. It also may be necessary to install resistances in short feeders. With such insulated track return feeders, part of the voltage drop is removed from the rails and is transferred to the insulated return feeders, from which cur-

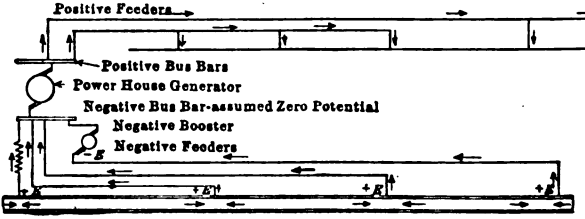


FIG. 130.—Insulated track-return feeder system.

rent cannot leak to ground. With this arrangement of insulated return feeders, the rails may be utilised as return conductors to the extent that the potential gradients and total track drops do not exceed safe limiting values.

A diagrammatic sketch of an insulated track return feeder system proportioned for equal drop is shown in Fig. 130. In this illustration it is assumed that the negative bus bar is at zero potential, and that the return-feeder

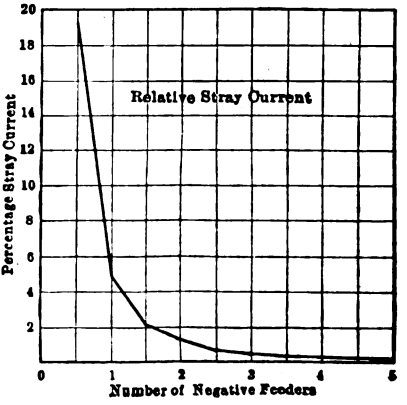


FIG. 131.

connection points on the rails are maintained at a potential of E volts with reference to the negative bus bar. Where a number of lines extend in different directions, the same arrangement of insulated return feeders must be applied to each of the lines. It should be observed that in this system the negative bus bar must not be connected to any ground contacts nor to the tracks in the neighborhood of the power station, except through suitable resistances; under these conditions the negative bus bar is said to be

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sulated. The possibilities of reducing stray currents by means of properly proportioned insulated return feeders as illustrated in Fig. 134 was clearly shown in a paper by Mr. George I. Rhodes (see bibliography). The diagram in Fig. 131 is reproduced from that paper. This shows the relative leakage currents with negative bus bar insulated and with various numbers of insulated return feeders proportioned for equal drop and connected to symmetrical points in the track. The points halfway between integral abscissas in Fig. 131, correspond to a connection between the negative bus bar and the rails at the power station, with a resistance in the connection proportioned to maintain this point in the rails at the same potential as the other return-feeder connection points. The unit of leakage current is assumed as the amount which flows when the negative bus bar is grounded through a negligible resistance, the rails being connected to the negative bus bar only at the power station. In practice each return feeder would actually be connected to a number of points in the rails in the immediate neighborhood of the connection points shown. See also Bureau of Standards Technologic Paper No. 52.

457. Examples of installations of insulated return feeder systems. Such systems are in common use in Germany and in Great Britain, and have given most satisfactory results. In America a considerable number of such systems have also been installed, the most prominent reported example being on the subway system of the Interborough Rapid Transit Company in New York City. Description of insulated return feeder systems installed in Springfield, Ohio, and in St. Louis, Mo., are given in Bureau of Standards Technologic Papers No. 27, No. 32 and No. 54.

458. Advantages of the insulated return feeder system. This system is intended to relieve the tracks of current by insulated conductors, and thus tends to prevent the escape of current into earth. With a properly laid out return feeder system and properly bonded tracks, it is possible and practicable to reduce stray currents through earth and therefore stray currents on underground piping and cable systems to any desired minimum values and such currents may be made so small as to be negligible.

ELECTROLYSIS FROM GROUNDED ELECTRICAL DISTRIBUTION SYSTEMS

459. Grounded neutrals in three-wire direct-current systems. Direct-current electric-lighting systems in which the distribution is on the Edison three-wire plan, having the neutral conductor grounded, are, in American practice, provided with such large neutral conductors of copper that only negligible stray currents are produced from such systems. This grounding of the neutral is intended to serve only as a safety measure, and is not for the purpose of using the earth to carry current.

460. Electrolysis from alternating currents. A large number of laboratory tests have been made to determine whether electrolysis is produced when an alternating current flows between a metal and an electrolyte, as for example between a pipe and surrounding soil. These indicate that slight electrolytic corrosion may be produced; this effect is generally less than 1 per cent. of that which would be produced by a corresponding direct current. With alternating current, however, electrolytic corrosion is produced at both electrodes, while with direct current, electrolytic corrosion occurs only at the positive electrode.

461. Grounded transformer secondaries. The secondaries of transformers are frequently grounded, for the purpose of preventing a high and dangerous voltage from existing between the secondary circuit and ground. Such ground connections however do not produce flow of current to ground, and such grounding of transformer secondaries therefore does not cause danger from electrolysis.

ELECTROLYSIS IN CONCRETE

462. General effects. Concrete when damp is an electrolytic conductor having a resistivity of the same order as damp soil. When iron is embedded in damp concrete and an electric current flows from the iron to the concrete, the iron may be oxidised by the electrolytic action. The oxides of iron formed occupy more space than the original iron, with the result that an outward pressure is produced which in time may crack the concrete. An exhaustive

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investigation of the effect of electrolysis on iron embedded in concrete has been made at the Bureau of Standards in Washington, and the results of this investigation are published in Technologic Paper No. 18 of the Bureau of Standards. This investigation appears to show that when no chlorides are present, the iron is practically passive at temperatures below 45 deg. cent but becomes active at higher temperatures. With large current densities, the heating effect of the current will destroy the passivity of the iron. When chlorides, even in very small amounts, are present, however, the iron is active at all current densities. These investigations also show that when current flows from the concrete to iron a softening of the concrete is produced close to the iron, which eventually destroys the bond between the two. Aside from slight and usually negligible heating, the only effect which an electric current has on unreinforced concrete is to cause a migration of the water soluble elements. Non-reinforced concrete structures are therefore immune from electrolysis trouble.

463. Reinforced-concrete structures. In order that a reinforced-concrete structure may be damaged by electrolysis, it is necessary that an electric current flow between the reinforcing steel and the surrounding concrete. Such current may be leakage current from a direct-current lighting system, or stray railway current brought into the building by means of service pipes. The conditions required for producing electrolysis of steel embedded in concrete are such, however, that this can result only in extreme cases; for example, where a direct contact is established between the reinforcing steel and one side of a direct-current lighting system, or where stray railway current of sufficient magnitude is brought by way of service pipes into contact with the reinforcing steel. It is therefore a safe precaution to install insulating joints in all pipes and lead-covered cables which lead to reinforced concrete structures from earth. It has been proposed to protect reinforced concrete by making the reinforcing steel continuous throughout, and connecting it to the negative terminal of a low-voltage generator. While this would prevent corrosion of the steel, it might result, however, in greater danger, on account of the possible destruction of the bond between the reinforcing steel and the concrete.

464. Structural foundations. Where steel foundations are embedded in concrete, it is important to guard against stray electric current reaching the steel from external sources and then flowing from the steel to the concrete, because corrosion of the foundation steel and cracking of the concrete may result.

MUNICIPAL AND STATE REGULATIONS

465. General. Municipal and state regulations, designed to minimize the escape of electric currents from electric railways using a grounded return circuit, generally attempt to limit the total allowable voltage drop and the allowable potential gradient in the grounded return circuit or grounded rails. Additional requirements limiting the total allowable current escaping from the system are included in some regulations. A few brief references to regulations which are at present in force, are given in Par. **466** to **469**.

466. British Board of Trade regulations. The two most important of these regulations are Regulations No. 7 and No. 8. The former limits the allowable difference of potential between any two points in the uninsulated return circuit to 7 volts, and requires that continuous records be kept by the railway company, of the difference of potential between certain points on the uninsulated return circuit. Regulation No. 8 limits the allowable current density in the rails to 9 amp. per sq. in. of cross-section (1.4 amperes per sq. cm.), which with ordinary steel is equivalent to an allowable potential gradient of approximately 0.8 volt per 1,000 ft. (0.305 km.) of rail.

467. German electrolysis regulations. In Germany a joint committee, representing the German Society of Gas and Water Engineers, the Society of German Electrical Engineers, and the Society of German Street Railway and Little Railway Managers, adopted in 1910 regulations for the protection of underground structures against electrolysis. The track network is divided into an inner district and an outer or suburban district. In interurban lines the parts near villages are designated as suburban districts. The potential difference between any two points on the track must not exceed 2.5 volts under average load conditions in the inner district, and on a bordering line

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2 km. (6,562 ft.) wide; outside this zone in the suburban districts, the voltage drop must not exceed 1 volt per kilometer (3,281 ft.).

468. American municipal ordinances. Some American cities have enacted ordinances designed to prevent damage by electrolysis. In 1912 the City of Chicago enacted an electrolysis ordinance, the most important feature of which is the voltage requirement, limiting the permissible difference of potential between any two points on the uninsulated return circuit to 12 volts, and limiting the potential gradient in the rails within 1-mile radius of the City Hall to 1 volt per 1,000 ft. (0.305 km.), and outside of this 1-mile radius to 1 volt in 700 ft. (0.213 km.). In 1913 the City of Chicago enacted what is known as the Unification Ordinance, which also contains clauses relating to electrolysis. These divide the city into three zones, and prescribe different voltage limitations for each zone. The Board of Supervising Engineers is, however, authorized to modify these voltage requirements in the third or outer zone. The above ordinances although not entirely in accord are both in effect in Chicago.

In a number of cities in Ohio electrolysis ordinances have been enacted in which the most important features are track voltage requirements. In these ordinances the average potential difference during any 10 consecutive minutes between any two points 1,000 ft. (0.305 km.) apart on the uninsulated return circuit must not exceed 1 volt, and the average potential difference during any 10 consecutive minutes between any two points more than 1,000 ft. (0.305 km.) apart on the uninsulated return circuit within the limits of the municipality must not exceed 7 volts.

469. Legal status of liability for electrolytic damage. There has been considerable litigation at various times with reference to damage from electrolysis. It has been held by various courts that no one utility can claim the exclusive right to use the earth as a return circuit, and that priority of such use is of no importance to either side of the controversy.

470. Peoria decision. In the celebrated Peoria case which was finally decided after having been in the courts for over 10 years, the railway company was enjoined and restrained from injuring the property of the water company by electric current escaping from the rails or structures of the railway company. No particular method for preventing escape of current is prescribed in the decree, because the court in its decision states that a court does not have the power to prescribe by injunction any specific system, and that this power resides only with legislative bodies. The decree also requires the water company to co-operate with the railway company to the extent of giving the railway company access to its piping system for the purpose of measuring flow of current upon its system and of determining whether injury from electrolysis is being continued, in order that the railway company may determine whether it is complying with the terms of the decree.

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SECTION 17

ELECTRIC VEHICLES

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SECTION 17

ELECTRIC VEHICLES

GENERAL CLASSIFICATION

1. The electric vehicle art prior to 1910 exhibited relatively little progress, due partly to the poor design of the earlier types of vehicles and partly to the comparatively heavy unsuited batteries. The art began to show considerable activity in 1910 and for the following four years the development of the passenger car progressed more rapidly than that of the commercial truck. However, the progress in the design and development of the gasoline passenger car, with its electrical starting and lighting system, higher speeds and practically unlimited radius of action, resulted in the diversion of popular attention from the electric passenger car to the gasoline passenger car. For this reason the number of manufacturers decreased steadily, until in the beginning of 1921 there were only two prominent makers of electric passenger cars.

2. Progress in commercial and industrial vehicles. The electric commercial and industrial trucks and tractors have progressed steadily since 1910 and have proved their economic worth in their particular fields in the transportation of merchandise.

3. Classification. Electric vehicles may be subdivided into three general classes according to character of service:

(1) Passenger cars.
(2) Commercial trucks and tractors.
(3) Industrial trucks and tractors.

The source of energy supply permits another classification, namely storage battery vehicles and the so-called trackless trolley which is a motor-propelled vehicle receiving its energy from an overhead trolley system. The storage-battery vehicle is by far the more important at the present time, as the highway trolley vehicle has not yet come into extended use in this country although it is employed to a limited extent abroad.

4. Scope of presentation. Due to the broad scope of design, the subject of electric vehicle engineering can be presented in the brief space available in an engineering handbook only with difficulty. An attempt has been made in this section to embody merely the fundamentals of the subject based on modern practice and so far as possible describe the most representative vehicle practices obtaining at present. Because of the variety of designs now being produced, it is impracticable to describe them all. Numerous types of vehicles have been designed for special purposes such as passenger and baggage transfer, cable pulling, crane tractors, pole hauling, dumping, baggage trucks, fire apparatus, etc., but practically all of these applications are specific and no attempt has been made to include them.

5. Features emphasized. It is particularly desired to point out that where descriptions of machines and accessories of various makes have been omitted, such omissions are due to the fact that limitations of space have confined the subject matter to those types which have gained prominence in industry or whose designs embody characteristics of particular interest to the engineer.

PASSENGER CARS

6. General features. The passenger vehicle involves no engineering features which do not conform to the fundamentals of vehicle engineering and their applications to commercial trucks as discussed under that caption.

7. Chassis and body. All cars are comprised of two principal elements: the chassis and the body. In general, the chassis comprises the frame, front and rear axles, complete with wheels, springs, steering gear, motor, power-transmission members, controller and battery. The plan view of a typical electric passenger-car chassis is shown in Fig. 1.

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8. The chassis frame is usually of pressed steel channel sections of liberal depth, with cross members for supporting the motor, battery compartment and other equipment forming a part of the vehicle.

9. The front axle is of drop-forged I-beam construction, providing maximum carrying capacity with minimum weight. The **steering knuckles** are, in general, drop-forged from alloy steel and heat treated.

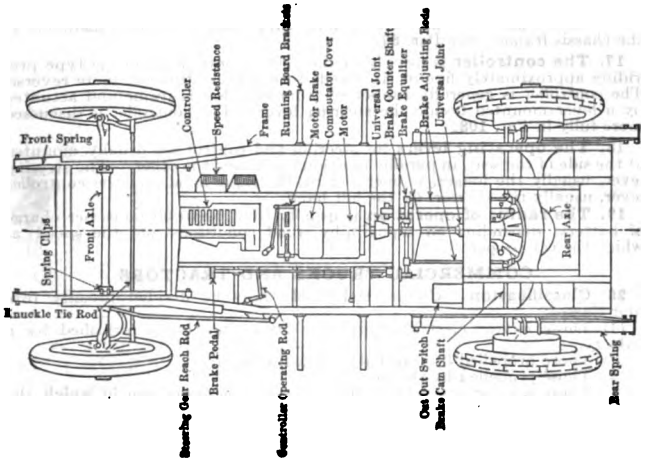


FIG. 1.—Plan view of Detroit electric chassis.

10. Power-transmission systems have in the past embodied various combinations of chain, spur and bevel gear, and worm drive. In the present-day designs, the rear axle is generally of the three-quarter floating type having either spiral bevel gears, with an approximate reduction of 5 to 1, or worm gearing with an approximate reduction of 9¾ to 1. Power is usually delivered from the motor to the rear axle through a propeller shaft having two dust-proof universal joints. The rear-axle torque is usually carried through a pressed steel member, pivotedly supported, to the chassis frame.

11. Two separate sets of brakes are usually provided, operating independently. The two sets are usually of one of the following combinations: (*a*) External contracting and internal expanding type mounted on the rear wheels and operated by foot pedals; (*b*) internal expanding type mounted on the rear wheels, operated by a foot pedal, and external contracting type mounted on the front end of the motor, fitted onto the armature or propeller shaft and operated by a backward movement of the controller lever or by a foot pedal. In some designs the application of the service brakes simultaneously interrupts the power circuit regardless of the position of the controller lever, making it impossible to start the car again until the controller lever has been returned to its neutral position.

Dynamic and regenerative braking have been tried in the past, but neither is in general use at present due to the complications that are introduced into the control system.

12. The springs are generally of chrome-vanadium heat-treated steel, the front being of the semi-elliptic type and the rear either the three-quarter elliptic or cantilever type.

13. The wheel base on cars of present-day design is usually 100 to 105 inches.

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14. The wheels are usually quick-detachable wood or wire type, designed for approximately 32 × 4½ in. cord pneumatic tires.

15. Batteries. Two prominent manufacturers specify their standard battery equipment to provide for 40 to 42 cells of 13 to 15 plate lead-acid battery. Vehicle batteries are discussed more fully in Par. 128.

16. The motor is usually a 4-pole series-wound machine, liberally designed to insure efficiency and ability to withstand overloads encountered under all operating conditions. The armature bearings of the motor are of the ball type. The motor is usually supported from cross members of the chassis frame. See Par. 87.

17. The controller is usually of the drum, continuous-torque type providing approximately five or six speeds forward and three or more reverse. The controller is generally supported from the chassis frame and actuated by a lever mounted beside the steering lever. The controller is discussed more fully in Par. 106.

18. The operating levers for steering and control are usually mounted at the side of the seat, in parallel position one above the other. The steering lever, usually the longer, is operated by the right hand and the controller lever, usually the shorter, by the left hand.

19. The radius of operation is usually from 60 to 90 miles per charge of battery, depending on topography, road conditions and the speed at which the car is operated.

COMMERCIAL TRUCKS AND TRACTORS

20. Classification. Commercial trucks may be divided broadly into four classes:

(1) Those having electric propulsion, the energy being furnished by a battery.

(2) Those propelled by internal combustion engines.

(3) Those propelled by steam.

(4) Those having gas-electric or steam-electric propulsion in which the energy of the prime mover is electrically transmitted to the axle or wheel.

21. Economic field of application. Each type of commercial truck has its distinct field of economic application, that of the electric vehicle being found in city delivery embracing the interchange of merchandise between railway terminals and docks, stores and factories, and retail deliveries. The electric vehicle possesses superior advantages over other means of merchandise transportation due to its inherent characteristics of rapid acceleration and retardation permitting it to maintain a high average speed and due further to its freedom from intricate mechanism for transmitting the motor energy to the wheels and the absence of numerous reciprocating parts.

22. Economic field of gasoline vehicle. The gasoline motor vehicle finds its best field of application in uninterrupted long-haul deliveries where the mileage exceeds that safely and conveniently obtained from the electric truck, its economic value being governed entirely by the individual characteristics of the particular business to which it is applied.

23. Economic field of electric vehicle. Electric trucks are more economical and satisfactory than gasoline trucks for approximately 85 per cent of all city haulage. The salient characteristics which contribute to the high efficiency and low operating costs of electric trucks are:

(*a*) The low cost of electrical energy.

(*b*) Operation at a safe economical speed.

(*c*) Ease of maintenance of battery service.

(*d*) Reliability and uniform driving power of the electric motor, which delivers maximum power to the rear wheels.

(*e*) Substantial construction and elimination of reciprocating members which almost wholly eliminate road troubles, reduce maintenance expense to a minimum and obviate the necessity for high-salaried mechanics.

(*f*) Minimum vibration and prevention of careless speeding prolong the life of the electric truck, and make it more than double that of a gasoline truck.

(*g*) The motor draws no energy from the battery when the brakes are applied or when the truck is coasting.

(*h*) Low cost of insurance.

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24. The chassis of the various makes differ only in some special features of design. The main frame members are comprised of rolled or pressed steel channels, with cross members secured to the side sills with either proper angle iron and gusset plates or integral gusset plates.

25. Representative types of chassis are illustrated in Fig. 2 and 3, showing respectively the side elevation and plan of a Ward one-ton chassis and a Walker 3½-ton chassis. Both of these types employ a single motor, the former with a worm-drive axle and the latter with a special balanced drive as described more fully in Par. **32**.

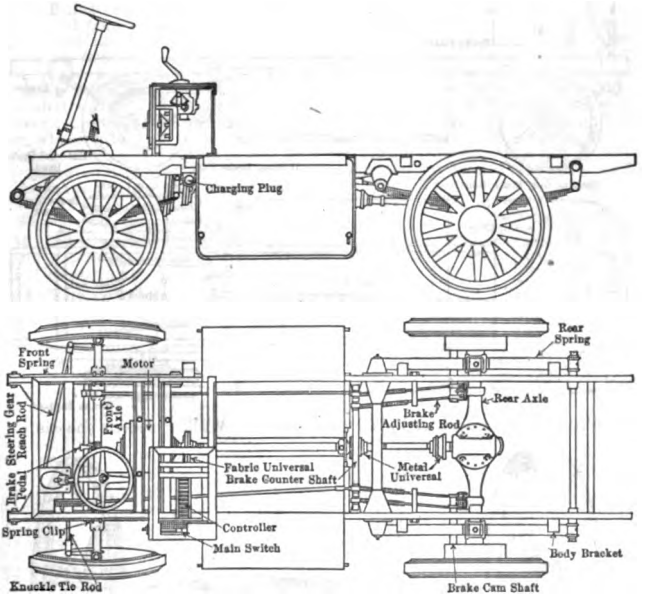


FIG. 2.—Elevation and plan view of 1-ton Ward electric chassis.

26. The battery compartment is usually carried amidship by structural steel members hung from the main chassis frame and having truss rods from the lower corners of the compartment to the side sills of the frame. In some cases the battery is mounted on top of the side frames and partly under the driver's seat. The underslung type of battery compartment has the following advantages: (*a*) Low center of gravity, resulting in less tendency when turning corners for the weight to be thrown from the inside to the outside wheels and therefore less tendency to skid; (*b*) the overall length of the truck is reduced, which enables the truck to be more easily operated in congested traffic zones and narrow places and requires less garage space; (*c*) permits the use of removable battery cradles and facilitates the interchange of batteries.

27. Springs. The front and rear springs are usually of the semi-elliptic type, of high-grade alloy steel, heat treated.

28. Axles. The front axles are usually of I-beam section, drop forged from high-grade steel, with drop-forged steering knuckles and steering knuckle arms. The rear axles embodying the transmission of the motor energy to the wheels differ in design on all the different makes of trucks.

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29. Transmission systems embody various combinations of chain, spur gear, bevel gear and worm drives. Considerable difference of opinion exists as to what constitutes the most desirable method of motor application and the best transmission design. The essential elements of a transmission comprise means of reducing the high speed of the motor to the comparatively

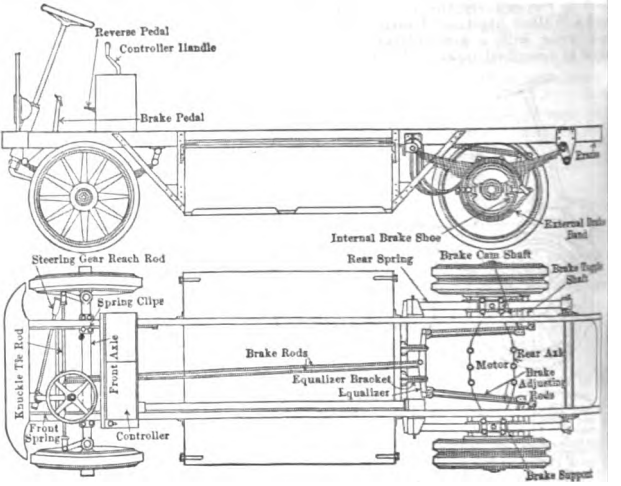


FIG. 3.—Elevation and plan view of 3½-ton Walker electric chassis.

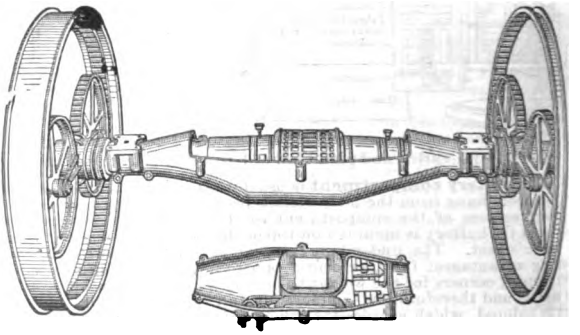


FIG. 4.—Rear axle assembly. Motor cover removed. (Walker Vehicle Company.)

low speed of the driving wheels and a differential gear which permits one wheel to turn faster than the other when the vehicle is propelled in a curved path.

30. The single-motor double-reduction chain drive is not extensively used by present-day manufacturers of electric trucks. It may still be found

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in operation on old vehicles in service in this country and on several makes of electric trucks manufactured in this country and in England.

31. The worm drive is usually of the semi-floating or full-floating type having the worm, worm wheel and differential and their bearings assembled as a unit with the cover. The housing is usually of cast steel reinforced by tubes. The road wheel is driven through a squared shaft and driving flange bolted to the hub, or through a splined shaft in the hubs of the differential gear and driving flange bolted to the wheel hub.

32. Balanced drive. In the Walker balanced drive, the motor, differential and transmission members are all embodied as parts of the rear axle and wheel assembly (Fig. 4). The power is transmitted through drive shafts to floating pinions within each wheel, then through intermediate spur gears housed within the disc wheels, to the internal gear which is pressed into and keyed to the wheel bands or rims. The drive pinions and shafts have no bearing, the pinions floating in a balanced manner between the idler gears with which they are constantly in mesh. The rear wheels are dirt- and water-proof and are partly filled with lubricant which is distributed continuously over all working parts. The rear wheels are mounted on roller or ball bearings supported by drop-forged steel stub axles secured in the ends of the hollow rear axle. The mechanical efficiency of this drive is very high, and stand tests indicate that efficiencies as high as 98 per cent. are obtainable.

33. The wheel-drive systems embodying constructions in which a motor drives each wheel separately and forms a more or less self-contained unit therewith are described in Par. **34** and **35**.

34. The couple gear drive, shown in Fig. 5, employs a motor mounted in a fixed horisontal position within the wheel itself, the axle stubs on which

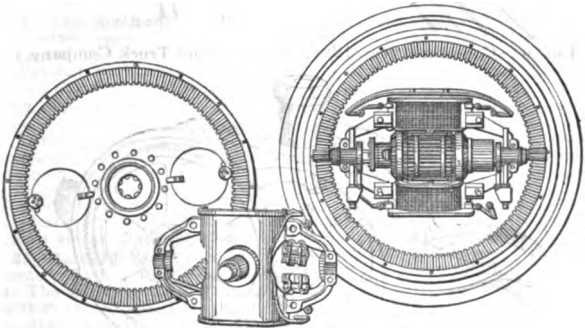


FIG. 5.—Wheel assembly, couple gear.

the wheel turns being integral with the motor castings. The armature shaft makes a slight angle with the plane of the wheel, permitting the bevel pinions mounted on each end of the armature shaft to mesh with their respective halves of a double cog rack near the periphery of the disc wheel. Thrust stresses arising from one bevel set are balanced by the other. This arrangement lends itself to four-wheel drive and steering.

35. Other wheel-drive systems which obviate the use of bevel gears and embody the double spur-gear reduction are shown in Figs. 6 and 7. These drives are used by the Commercial Truck Company. In the concentric gear drive illustrated in Fig. 6, the gear cases are mounted between two axle members, the extension of the case forming the axle spindle. The motor is bolted to the inner side of the gear case in a fixed position and in line with the axle. The armature pinion engages three spur gears, which are carried by studs mounted integral with the driving shaft. The pinions

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which are integral with the intermediate gears, as shown in Fig. 6, engage a single gear which is pressed into and keyed to the gear case. The driving shaft passes through the axle spindle and connects with the outer end of the wheel hub through the hub cap. The driving shaft has no bearing in the axle spindle, the driving gears and driving shaft being supported and held in proper position in the following manner: The double intermediate gear has a cylindrical extension formed on its inner end having a diameter equal to the pitch diameter of the small gear. A cylindrical track is formed in

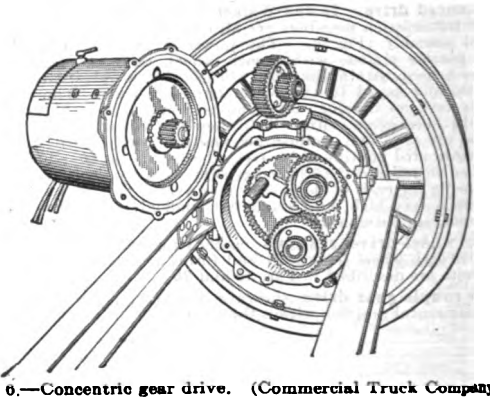


FIG. 6.—Concentric gear drive. (Commercial Truck Company.)

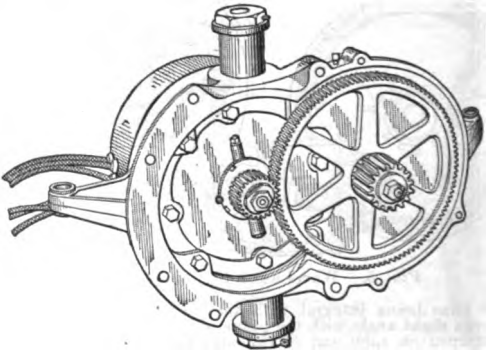


FIG. 7.—Double spur-gear reduction drive. (Commercial Truck Company.)

the motor head, the diameter of which is equal to the pitch diameter of the internal gear. It will thus be seen that the three bearings form a rolling support for the inner end of the driving system, the outer end of the driving shaft being supported and held centrally by the hub shaft. The gear case is oil and dust tight, the gears running continuously in a bath of oil. This drive is used on trucks of ½-ton, 1-ton and 2-ton capacity.

In the double-reduction spur gear drive illustrated in Fig. 7 the motor, which is a standard truck type, series wound, with a cylindrical steel frame, is carried in a steel casting accurately bored to a size that will allow the

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motor to be slipped freely in place up to a definite shoulder. The case is split partly around and horizontally, so that by tightening bolts through the lugs cast on this part of the case, the case can be securely clamped around the outside of the motor. The gearing between the motor and the wheel consists of straight spur gears. The first pinion is mounted directly on the tapered armature shaft with a key. The double intermediate gear is carried by a roller bearing on an intermediate stud, which is supported in the same casting that carries the motor. The intermediate pinion engages an internal gear mounted directly on the wheel hub, the outside surface of the internal gear forming the brake drum. The axle spindle is constructed so as to form an extension of the gear and motor case, the spindle being approximately in line with the center of the motor. A concentric flange, which is bored to a diameter slightly larger than the outside of the internal gear and provided with grooves, forms a dust and grease type joint. Trunnions integral with the gear and motor case located at the top and bottom, as shown in Fig. 7, are arranged to engage the axle ends and form a knuckle construction for steering the motor wheel as a unit. The gearing is entirely enclosed and the gear case is partly filled with a heavy grease. The axles are steel forgings and are made in two parts separated by a spacer forming the equivalent of a deep I-beam section. The axle forgings are enlarged at the ends and bored out and bushed to receive the trunnions before described, which are part of the motor casing. The axle with the motor casing thus forms a knuckle construction for steering, a thrust ball-bearing being mounted in the front top axle at the trunnions. The assembly of the front and rear constructions is the same, with the exception of the ball bearings. The motor wheels of the front construction are connected by the usual cross rod with the steering rod or drive link connecting one of the motor wheels to the steering gear. The motor wheels of the rear construction are secured in a fixed relation to the axle, the wheels being rigidly mounted. This drive is used on trucks of 3½- and 5-ton capacity.

36. The methods of providing for torsion and propulsion stresses in electric trucks follow the same general practice which prevails in the design of gasoline trucks. The discussion of these methods cannot be undertaken within the space available, and therefore the reader is referred to any standard treatise on the design of gasoline motor trucks.

37. The brakes in general conform in design to the accepted practices of gasoline motor truck brakes. Two independent brake systems are usually furnished, one being an external contracting-type brake on the rear wheel functioning as a service brake and the other being an internal expanding brake on the rear wheel functioning as an emergency brake. In some cases both brakes are of the internal expanding type on the rear wheel and in other cases an external contracting-type brake on the propeller shaft is furnished in addition to an internal expanding-type brake on the rear wheels. The brakes are generally operated by foot pedals.

38. Battery requirements. A storage battery to fulfill the requirements of truck propulsion should have the following characteristics: (*a*) The ability to propel a loaded truck up the gradients encountered in service; (*b*) it should be efficient; (*c*) it should be rugged and substantial in construction and capable of withstanding the severe shocks of service; (*d*) it should have the ability to give a long period of useful service; (*e*) it should have ample capacity for the application involved.

The recommendation of the Society of Automotive Engineers regarding number of battery cells is as follows: The number of cells in lead-acid batteries shall be 42, and the number of cells in the nickel-iron alkaline type 60. In many cases 44-cell batteries cannot be properly charged on account of the low voltage of the current supply. The 42-cell battery can be divided to make a more convenient arrangement of trays. See Par. 128 *et seq.*

39. Motors. One motor of the four-pole series-wound type is usually employed to propel a truck, although in some applications two or four motors are used. Motors are discussed more fully under Par. 87 to 107.

40. Controllers are discussed more fully under the caption "Controllers," Par. 128 to 132.

41. Tires. The function of the tires is to provide traction, prevent slippage, protect the mechanism of the vehicle from shock and vibration and cushion the load. In general all electric trucks are equipped with solid

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tires. The carrying capacity of solid tires as specified in the standards of the Society of Automotive Engineers is given in Par. 42.

42. Sizes and Carrying Capacity of Solid Tires
(S. A. E. Standard)

Nominal tire size		Min. total sectional area of rubber (1) (sq. in.)	Carrying capacity (lb.)
In.	Mm.		
32 × 3	75/660	5.00	1,000
36 × 3	75/762	5.00	1,000
32 × 3½	90/660	6.75	1,300
34 × 3½	90/711	6.75	1,300
36 × 3½	90/762	6.75	1,300
32 × 4	100/660	7.75	1,700
34 × 4	100/711	7.75	1,700
36 × 4 (2)	100/762	7.75	1,700
34 × 5	125/711	10.75	2,500
36 × 5 (2)	125/762	10.75	2,500
40 × 5 (3)	125/864	10.75	3,000
34 × 6	150/711	13.75	3,500
36 × 6	150/762	13.75	3,500
40 × 6 (3)	150/864	13.75	4,000
34 × 7	175/711	16.75	4,500
36 × 7	175/762	16.75	4,500
40 × 7 (3)	175/864	16.75	5,000
36 × 8 (4)	200/762	19.75	5,500
36 × 10 (4)	250/762	25.75	7,500
40 × 10 (4)	250/864	25.75	8,000
40 × 12 (4)	300/864	31.75	10,000
40 × 14 (4)	350/864	37.75	12,000

(1) Includes both hard and soft rubber.
(2) Single tires for single and dual wheels.
(3) Dual tires for dual wheels.
(4) Single tires for dual wheels.

43. Instruments. The type of instrument now in general use on electric trucks is the ampere-hour meter. This instrument gives a visual indication of the condition of charge of the battery, both while operating the vehicle and while charging, and also facilitates automatic charging.

44. The rating of electric trucks, according to the recommendations of the Society of Automotive Engineers, is as follows:

Speed rating. The electric-vehicle speed rating shall be based on continuous operation with one-half load over hard, smooth and level roads or pavements at the average battery voltage.

Mileage rating. The electric-vehicle mileage rating shall be based on a continuous run at the S. A. E. rated speed with one-half load over hard, smooth and level roads or pavements.

45. Commercial tractors are identical in design with the commercial truck, except as regards the mounting of the battery, shorter wheel base and lower operating speeds. Tractors may be generally subdivided into three classes:

(1) Trailer type.
(2) Semi-trailer type.
(3) Crane type.

46. The trailer type of tractor comprises those equipped with spring draw bars or pintle hooks, designed to haul a trailer or a train of trailers. In this type the battery is generally mounted in a steel compartment on top of the frame side sills. This type is usually capable of hauling a trailing load of ten to twenty tons gross weight.

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Load capacity	Make and model	Chassis, wt. in lb. (excluding battery)	Approx. body allowance in lb.	Approximate battery equipment			Max. speed, m.p.h.	Max. mileage per charge
				No. cells	Make	Type		
750 lb.	Ward, WS2	1,500	500	60	Edison	A4	13	45
				42	I. C. Exide	MV9		
				42	Phila.	WMT9		
1,000 lb.	Com. Truck, BR1	2,000	600	60	Edison	A5	14	60
	Walker, M	2,300	600	42	I. C. Exide	MV11	15	60
				42	Phila.	WMT13		
1,250 lb.	Ward, WA	2,730	800	60	Edison	A5	12	45
1,500 lb.	Com. Truck, BR2A	2,200	800	42	I. C. Exide	MV11	14	60
	Lansden, BG½	1,700	800	42	Phila.	WMT13	15	50
2,000 lb.	Atlantic, IC	2,770	1,200				12	.....
	Com. Truck, BR2	2,400	1,200	60	Edison	A6	14	60
	Lansden, MC1	2,900	1,200	42	I. C. Exide	MV13	12	50
	Walker, K	2,700	1,200	42	Phila.	WMT15	14	60
	Ward, WB	3,430	1,200				10	40
4,000 lb.	Atlantic, 2C	3,590	1,500				11	40
	Com. Truck, BR4	4,000	1,500	60	Edison	A8	12	60
	Lansden, MD2	4,400	1,500	42	I. C. Exide	MV15	11	40
	Walker, L	3,700	1,500	42	Phila.	WMT17	13	60
	Ward, WD	4,500	1,500				8.5	35
7,000 lb.	Atlantic, 3C	5,220	2,000				10	.....
	Com. Truck, AK7	5,800	2,000	60	Edison	A10	11	50
	Lansden, ME3½	5,700	2,000	42	I. C. Exide	MV19	10	45
	Ward, WF	6,600	2,000	42	Phila.	WMT23	7	30
	Couple gear, H	9,000	2,000				10	30
	Walker, P	5,500	2,000				11	50
10,000 lb.	Atlantic, 5C	6,230	2,500				9	.....
	Couple gear, H	10,000	2,500	60	Edison	A12	7	30
	Com. Truck, AK10	6,500	2,500	42	I. C. Exide	MV21	10	50
	Lansden, MT5	7,500	2,500	42	Phila.	WMT25	10	40
	Walker, N	6,400	2,500				10	50
	Ward, WH	8,375	2,500				6	26
Haulage tractor	Walker, 3	4,500	.....	60	Edison	A12	10	.....
Fifth wheel tractor	Walker, 5	6,000	.....	42	I. C. Exide	MV25	10	.....
Crane tractor	Walker, 7	7,200	.....	42	Phila.	WMT29	10	.....

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Load capacity	Make and model	Controller speeds, forward	Tires		Std. wheel base, in.	Per cent. wt. on rear tires	Type of drive
			Front	Rear			
750 lb.	Ward, WS2	4	32×3	32× 3	88	60	Worm
1,000 lb.	Com. Truck, BR1	4	36×3½	36× 3½	89½	60	Com. truck conc. gear
	Walker, M	5	34×3	36× 3½	94	66	Walker balanced
1,250 lb.	Ward, WA	4	32×3	34× 3½	90	60	Worm
1,500 lb.	Com. Truck, BR2A	4	36×3	36× 3½	92	60	Com. truck. conc. gear
	Lansden, BG½	4	32×4½*	32× 4½*	90	50	Double red. gear
2,000 lb.	Atlantic, 1C	4	34×4	36× 4	103	65	Chain
	Com. Truck, BR2	4	36×3½	36× 4	101	60	Com. truck conc. gear
	Lansden, MC1	4	36×3	36× 3½	108	60	Chain
	Walker, K	5	34×3½	36× 4	101	66	Walker balanced
	Ward, WB	4	34×3½	36× 4	102	60	Worm
4,000 lb.	Atlantic, 2C	4	34×4	36× 3†	115	65	Chain
	Com. Truck, BR4	4	36×4	36× 4†	116	60	Com. truck conc. gear
	Lansden, MD2	4	36×4	36× 3†	120	60	Chain
	Walker, L	5	38×4	38× 6	112	68	Walker balanced
	Ward, WD	4	36×4	36× 7	114	60	Worm
7,000 lb.	Atlantic, 3C	5	36×5	40× 5†	135	65	Chain
	Com. Truck, AK7	4	36×6	36× 4†	122	55	Com. truck. dbl. sp. gear
	Lansden, ME3½	4	36×5	36× 4†	133	60	Chain
	Ward, WF	5	36×5	36× 8	132	70	Worm
	Couple gear, H		36×6	36× 8	96	55	Couple gear wheel
	Walker, P	5	36×5	40× 5†	131	71	Walker balanced
10,000 lb.	Atlantic, 5C	5	36×6	40× 5†	144	65	Chain
	Couple gear, H	5	36×6	36× 8	132	75	Couple gear wheel
	Com. Truck, AK10	4	36×7	36× 5†	132	55	Com. truck. dbl. spur gear
	Lansden, MT5	4	36×6	36× 5†	146	60	Chain
	Walker, N	5	36×6	40× 6†	141	74	Walker balanced
	Ward, WH	5	36×7	40×10	144	70	Worm
Haulage tractor	Walker, 3	5	34×4	40× 6	170		Walker balanced
Fifth wheel tractor	Walker, 5	5	36×5	40× 6†	140		Walker balanced
					87		Walker balanced

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48. The semi-trailer type of tractor comprises those equipped with fifth wheels, trailer attachments, or swivel connections, designed to haul a semi-trailer. The battery is generally underslung amidship, with sometimes a portion of it mounted directly behind the cab on top of the frame side sills. This type is usually designed to haul a semi-trailer of ten tons gross weight, one-third of the total trailer weight being carried by the rear end of the tractor.

49. The crane type of tractor is equipped with an electrically-operated hoist, with either fixed or swinging boom, designed to carry one ton on the hoist hook, or to hoist two tons with tractor stationary and sprags set. In addition, this type is usually equipped with spring drawbar or pintle hook for hauling trailers.

50. Commercial specifications of trucks and tractors. The principal characteristics of various types of commercial trucks and tractors are given in detail in Par. 47.

INDUSTRIAL TRUCKS AND TRACTORS

51. Systems of trucking. Three standard systems of storage-battery industrial trucking are in use. The choice of industrial trucks or tractors to meet the particular requirements of any industry should be based on a careful analysis for the purpose of determining which system will best meet the existing or contemplated arrangement of buildings and departments and general transportation facilities. The three systems are:

1. Platform hauling, in which the truck is required to wait while being loaded and unloaded by hand, gravity or crane.
2. Electric self-loading and self-unloading, or semi-self-loading and unloading.
   (*a*) Electric lifting platform and tiering trucks, which eliminate loading and unloading by means of false platforms or skids.
   (*b*) Semi-self-loading or unloading trucks such as crane and hopper trucks.
3. Tractor-trailer systems in which the power unit is coupled to and draws one or more unit loads on wheels, either singly or in trains.

52. Platform trucks are in more general use because of the fact that for most installations the commodities are mixed in character. These trucks are manufactured in numerous models or designs, from which the most suitable type may be selected for a particular application. Among the important factors in making a selection are the height, width and length of the truck desired. The proper height of the platform is dependent, in general, upon the character of the material to be loaded. Standard heights of truck-loading platforms are 12, 17, 18, 20, 24 and 33 in. The character of the runways or roads over which the truck will travel may affect the size of the wheels and consequently the height. The higher platforms are to facilitate the loading of baggage, mail, express, or the like, from car floors and the loading of castings and other heavy materials by means of cranes.

53. The battery mounting in low-platform types is over the driving axle at one end, enabling the use of wheels of small diameter at the other end beneath the low loading platform.

54. The battery mounting in high-platform type is beneath the loading platform. The wheels are of the same size, thus providing ample clearance under the truck. This design provides maximum loading space.

55. Width. The question of width is determined by the aisle, doorway and equipment clearances. With trucks which employ four-wheel steering, the question of clearance is of lesser importance because of the greater flexibility in handling. The standard widths of trucks are 30, 37, 40 and 45 in. The wheel treads should be such as to provide ample stability under all conditions of operation.

56. Length. The length of the standard trucks is dependent upon the character of merchandise to be transported, but the wheel base should not be so long as to impair adaptability. In some cases the ability to control the truck from either end will provide the greatest flexibility in operation.

57. Folding platforms for the operators to stand upon and adjustable end gates facilitate the operation of trucks in congested zones, on elevators and in freight cars.

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58. Steering and wheel drive. Trucks are designed for two-whee drive, with two-wheel steering; four-wheel drive, with four-wheel steering or two-wheel drive with four-wheel steering.

59. The self-loading and self-unloading types of industrial truc equipment comprise the elevating platform, tiering, crane and hopper trucks the most popular type being perhaps the electric lifting or elevating pla form type.

60. The elevating-platform type of truck is fitted with a lifting pla form having a carrying capacity of 4,000 lb. The platform proper is raise and lowered by an electric motor and is designed to run under low portab platforms which are electrically lifted by the platform of the truck and s down without necessity of rehandling. The height of the lift is general 3 to 5 in. with 4,000-lb. load. The lifting mechanism is operated by independent motor supplied from the storage battery which propels t truck.

61. Worm lift. In this type the lift is effected by means of a steel worm The load when raised is sustained on a horizontal plane which takes t entire strain off the lifting mechanism.

62. Screw lift with rocking platform. In this type a motor is dire connected to a worm and gear for driving the elevating mechanism. Th spider on which this gear is mounted forms a special clutch adjusted to sli at a fixed overload, in such manner that if the load should catch under a obstruction when lifting, the motor with gear and worm will rotate harm lessly. This clutch is threaded at the center and, when revolving, prope a square multi-thread screw in or out, depending on the direction of mot rotation. The entire mechanism is enclosed in an oil-tight malleable cas The extension of the screw shaft is attached flexibly to the platform on whi the load is lifted. The platform is mounted on two heavy links at the re and one at the front end, providing a three-point support. The actio of the screw draws or thrusts the platform backward and upward until t links become practically vertical and raise the load 4½ in. Guides attache beneath the platform steady the load when raised.

A travel limit rod is connected with the motor reversing switch and ope the circuit when the platform reaches either the upper or lower limit o travel. Whenever the motor switch is opened, a special brake on the s of the armature shaft quickly stops the mechanism. The principal adva tage of this type is the fact that the operator is able to perform all the lab of loading, transfer and unloading without difficulty.

63. Tiering type. The tiering lifting truck is similar to the elevatin platform type (Par. 60) with the exception that the loads may be lifted a distance from 1 in. to 6 ft. or more, thus making the truck a combinatio electric-lifting platform truck and tiering machine. This type also has carrying and raising capacity of 4,000 lb. It will mechanically pick u transport and deposit its load without the necessity of rehandling, and to certain extent will perform the work of a portable crane.

64. Crane type. A crane truck embodying an electrically-operat hoist and boom crane mounted on a standard electric platform truck useful for handling and moving heavy materials or machinery which a not within range of the usual travelling cranes. This type extends th service of the traveling-crane or mono-rail system to the yards or to adj cent buildings where the construction and head room restrict the use of overhead carrier. Crane trucks are built for lifting capacities of 1,000, 2,00 and 3,000 lb. The boom may be raised or lowered to permit landing th load at any point on the platform of the truck. The boom is also equippe with a swivel base so that it may be swung to either side.

65. Hopper trucks for the handling of coal, ashes, sand and simil materials are in general built in two types, comprising the double side dum and the end dump. In some of the end-dump types the hopper can b dumped by a separate motor energised from the truck battery.

66. The tractor-trailer system of inter-plant transportation ha proved to be the more economical and adaptable type of transfer unit whe heavy drawbar pull is required and where large tonnage is to be handle daily. This system is comprised of a power unit and as many individu trailers without motive power as may be required. Although any type

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truck may be used to haul trailers singly or in trains, the battery capacity is usually insufficient for the continuity of service required.

67. The tractor power unit may be kept in operation almost continuously and does not have to remain idle during the loading and unloading operations, as is the case with load-carrying trucks.

68. Use of the truck as a tractor. Any type of truck may be used to draw trailers, but in general the battery capacity is insufficient for continuous service and trucks as a class are not designed with the necessary drawbar pull for this work. The drawbar pull depends directly upon the weight on the driving wheels and the torque capacity of the motor.

69. Drawbar pull. The normal drawbar pull is the maximum rating under which the tractors are designed to operate continuously, assuming average conditions. The maximum drawbar pull is attained just before the driving wheels begin to slip. The total load in tons which can be moved, including weight of trailers, may be calculated on the basis of 50 lb. drawbar pull per ton, assuming trailers with good bearings traveling on level dry brick, concrete or wood floors.

70. Steering and wheel drive. Tractors are equipped with two-wheel drive, with single-wheel, two-wheel or three-wheel steering, depending upon the type.

71. The frame design follows generally-accepted automotive practice very closely. The frames are made of I-beams, heavy channels, or angle-iron sections, depending on the type of truck or tractor. The frame is supported on the axles either by heavy coil springs or by semi-elliptic springs.

72. Wheel construction. Wheels in general are of the solid or cast type, revolving on roller or ball bearings and equipped with either solid pressed-on rubber or fabric tires. The carrying capacity of solid tires recommended in the Standards of the Society of Automotive Engineers is given in Par. **73.**

73. Industrial Truck Tires
(S. A. E. Standard)

Nominal tire sizes		Wheel dimensions	
Nominal diameter (in.)	Width (in.)	Diameter (in.)	Felloe width (in.)
10	3½	6	2½
10	5	6	4½
16	3½	12	2½
16	5	12	4½
20	3½	16	2½
20	5	16	4½
24	3½	20	2½
28	3½	24	2½

Wheel diameters shall be 4 in. less than the nominal tire diameters.
The height of the finished tire shall be 2 in. for all sizes.

74. Axles and housings. The axles and housings are made of steel and conform to standard automotive design practice.

75. Transmission. The types of transmission in general use include the worm, chain and spur-gear drives.

76. The chain drive consists of a driving pinion on the motor shaft which engages a sprocket wheel through a silent chain. This sprocket, embodying a compact differential, transmits the mechanical energy through a steel countershaft to sprockets at either end, which in turn engage sprocket wheels on the respective driving wheels by means of roller chains.

77. The worm drive consists of a high-grade steel worm, phosphor bronze wormwheel and differential, with all bearings assembled as a unit in a cast-steel housing, each road wheel being driven through a shaft. All power-transmitting parts are in oil-tight housings and operate in a bath of oil.

78. The spur-gear drive in general comprises a double-reduction spur gear, entirely enclosed and operating in oil.

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79. Approximate Specifications of Various Types of Industrial Trucks

Make and model	Capacity in pounds	Weight with Edison battery (lb.)	Weight with Lead battery (lb.)	Drive	No. steering wheels	No. driving wheels	Wheel base (in.)	Tire size (in.) Driving wheels	Tire size (in.) Other wheels
Automatic, R	2,000	1,200	1,400	Worm	2	2	36	16 ×3½	16 ×3½
D	4,000	1,700	1,910	Chain	2	2	39	16	16
E	4,000	2,870	2,980	Worm	2 or 4	2	60	16 or 20	16 or 20
E	4,000	2,300	2,425	Chain	2	2	53	16	16
H	4,000	2,380	2,430	Worm	4	2	53	20 ×3½	9 ×5
H	4,000	2,300	2,350	Gear	4	2	51	16 ×3½	9 ×5
Drop frame bag	4,000	3,250	3,360	Worm	4	2	102	27 ×3½	27 ×3½
Straight frame bag	4,000	3,550	3,660	Worm	4	2	96	27 ×3½	27 ×3½
L	4,000	2,800	2,900	Worm	4	2	54	20 ×3½	9 ×5
L	4,000	2,700	2,750	Gear	4	2	51	16 ×3½	9 ×5
Tiering	4,000	3,450	3,600	Worm	4	2	56	20 ×3½	9 ×5
E crane	4,000	4,070	4,180	Worm	2 or 4	2	60	16 or 20	16 or 20
H crane	4,000	2,440	2,590	Gears	4	2	50	19 ×5	16 ×3½
Elwell Parker, WB	4,000	2,500	2,625	Worm	4	2	78	21½ ×3½	15 ×3½
FC	4,000	2,400	2,525	Worm	4	2	53	21½ ×3½	15 ×3½
IE	3,000	1,800	1,900	Worm	4	2	37	15 ×3½	15 ×3½
ID	4,000	2,050	2,100	Worm	4	2	67	15 ×3½	15 ×3½
IY	4,000	2,450	2,575	Worm	4	2	53	20 ×3½	20 ×3½
IX	4,000	2,700	2,825	Worm	4	4	53	20 ×3½	20 ×3½
Straight frame, S.E., bag	4,000	3,200	3,325	Worm	4	2	85	27½ ×3½	27½ ×3½
Drop frame, D.C., bag	4,000	3,250	3,375	Worm	4	2	116	27½ ×3½	27½ ×3½
C.F. crane	4,000	5,075	5,200	Worm	4	2	78	21½ ×3½	15 ×3½
E.H., self-klg	4,000	2,825	2,950	Worm	4	2	58	21½ ×3½	15 ×3½
E.C., self-klg	4,000	2,800	2,925	Worm	4	2	58	21½ ×3½	15 ×3½

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Make and model	Loading platform			Control		Max. speed, m.p.h.	Max. turning radii		Max. overall dimensions	
	Length (in.)	Width (in.)	Height (in.)	Single or double end	No. speeds		Outside (in.)	Inside (in.)	Length (in.)	Width (in.)
Automatic, R	64	29	20	S	2	5	77	24	83	29
D	61	36	20	S	3	5½	106	42	92	38
E	98	41	22–24	S	3	7	178–108	119–49	118	41
E	79	41	20	S	3	8	155	93	117	41
H	64	41	12	S	3	6	98	44	104	41
H	63	41	12	S	3	6	113	57	102	41
Drop frame bag	144	44	11	D	3	6	.....	.....	170	44
Straight frame bag	144	44	33	D	3	6	.....	.....	170	44
L	52	24	10	S	3	6	95	48	103	38
L	55	24	10	S	3	6	.....	.....	103	42
Tiering	52	26	10–95	S	3	6	93	40	117	38
E crane	60	41	23–25	S	3	7	178	119	118	51
H crane	.....	41	12	S	3	6	122	51	102	41
Elwell Parker, WB	93	40	17	S	3	5½	111	53	137	40
FC	56	40	13	S	3	5½	184	36	100	40
IE	48	30	20	S	3	6½	96	45	80	30
ID	88	37	18	S	3	5½	105	53	112	37
IY	83	40	24	S	3	5½	96	38	107	40
IX	83	40	24	S	3	5	96	38	107	40
Straight frame, S.E., Bag	137	44	33	D	3	6	156	90	164	45
Drop frame, D.G., bag	137	44	11	D	3	6	198	140	165	45
C.F. crane	.....	40	17	S	3	5	111	53	137	40
E.H., self-ldg	54	26	17	S	3	5½	92	40	105	36
E.G., self-ldg	54	26	11	S	3	5½	92	40	105	36

NOTE.—The battery, in general, is comprised of 21 cells Edison A6, or 12 cells lead battery, of 196 to 220 amp.-hr. capacity.

80. Approximate Specifications of Various Types of Industrial Tractors

Make and model	Drawbar pull (lb.)		Weight (lb.)		Drive	Battery equipment				Speeds	
						Edison		Lead			
	Rated	Max.	With Edison battery	With lead battery		No. cells	Amp.-hr. capacity	No. cells	Amp.-hr. capacity	No.	Max. m.p.h.
Automatic, T	600	1,600	2,550	2,750	Worm	.....	.....	.....	.....	3	6
D	250	1,000	2,010	2,420	Chain	.....	.....	.....	.....	3	6
M	800	2,000	3,300	3,525	Worm	.....	.....	.....	.....	3	.....
MT	300	1,200	2,500	2,910	Chain	.....	.....	.....	.....	3	5½
Elwell Parker, TC	400	1,700	3,350	3,600	Worm	42	225	24	196–220	3	5
TA	300	1,300	2,400	2,450	Worm	30	225	16	196–220	3	7½
TM	400	2,400	4,000	4,250	Worm	42	225–300	24	196–280	3	6
Mercury	600–750	600–750	1,980 2,270	2,180 2,560	Worm	30	225–300	18	220–315	3	7½
	1,500	1,500	2,450 2,770	2,660 2,950	Worm	42	225–300	24	220–315	3	7½

Make and model	No. steering wheels	No. driving wheels	Tire sizes (in.)		Wheel base (in.)	Overall dimensions (in.)			Turning radii	
			Driving	Other		Length	Width	Height	Outside (in.)	Inside (in.)
Automatic, T	1	2	16	16	42	72	40	53	122	51
D	2	2	16	16	39	76	38	55	101	54
M	2 or 4	2 or 4	16 or 20	16 or 20	44	85	40	49	136	74
MT	2	2	16	16	39	71	38	49	108	24
Elwell Parker, TC	4	2	15×5	15×3½	38	88	39	52	75	25
TA	1	2	20×3½	15×3½	40	70	41	52	64	7
TM	2	2	20×5	20×3½	45	87	41	52	68	18
Mercury	½	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	97 71	.....

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81. Motors are usually of the 24-volt or 48-volt classification. In worm-drive types the motor is in general mounted so that it can be connected directly to the shaft of the worm. In chain-drive types, and in some worm-drive types, the motor is supported from the chassis frame. See Par. 87 to 107 for details.

82. The controller is usually mounted either on the front of the truck, where it is accessible and readily coupled to the operating mechanism, or underneath the platform and operated by a series of levers and bell cranks. When installed on the front of the truck it can be mounted with the shaft either horisontal or vertical, as desired. The motion of the controller handle is up and down, with horisontal shaft mounting, and right and left with vertical mounting.

83. The safety switch usually serves two purposes as follows: (1) It is operated by the brake pedal, which is spring set, so that when the operator leaves the truck the circuit of the motor is opened and the brake applied; (2) the safety switch is usually so interlocked with the controller drum that the latter must be returned to the "off" position before the safety switch can be closed or the brake released.

84. Interlocking features. Downward pressure of the operator's foot closes the safety switch (Par. 83) and releases the brake, after which the controller drum can be rotated to any desired position. If the brake be applied, the safety switch opens and the truck stops. The power cannot again be applied until the controller handle is moved to the "off" position. This is known as the **"off-position interlock."** In some applications it is possible to close the safety switch and release the brake with the controller handle in the first position, that is, power can be applied as soon as the brake is released, to prevent losing control of the truck if it is standing on a grade. This is what is known as the **"first-position interlock."** One objection to the latter type of interlock is that the truck can be left standing with the controller handle in the first position and the brake applied, so that an operator returning to the truck and closing the safety switch and releasing the brake without first returning the controller handle to the "off" position would unintentionally start the truck. With the "off-position interlock," the operator must return the control handle to the "off position," before he can release the brake and close the safety switch, this preventing unintentional starting. The "off-position interlock" permits the truck to start without power on a grade, whereas the "first-position interlock" gives complete control on a grade. However, with the former scheme an additional emergency brake can be provided, which, when released, closes the safety switch and allows the controller handle to be moved to the first position.

85. The brake is mounted on the worm shaft or wheels. Braking is effected by a contacting type of brake shoe lined with woven asbestos, actuated by a spring and released by a foot pedal or the operator's platform. In the case of tractors, the brake is sometimes actuated by a spring controlled by the driver's seat, so that the brake is automatically set whenever the driver leaves his seat.

86. The principal characteristics of various commercial types of trucks and tractors are given in the tables in Par. 79 and 80.

VEHICLE MOTORS

87. Speed-torque characteristic. The inherent characteristic of the motive power for vehicle propulsion should be an increase in effort with decrease in speed. The series motor has this operating characteristic, since its speed varies as an inverse function of the torque, or turning effort. It likewise has a high value of torque per ampere drawn from the battery, throughout its range of operation.

88. Field coils. At present practically all series motors for vehicle service have four field coils, arranged in two pairs, each pair being connected permanently in series. These pairs are arranged normally for connection in series and in parallel. In some special cases, the motors have six field coils instead of four.

89. Type of speed characteristic. The typical speed characteristics of vehicle motors are as follows: (*a*) Flat speed characteristic, in which the speed does not drop rapidly on overloads; (*b*) steep speed characteristic, in

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which the speed drops rapidly on overloads. A motor having a flat speed characteristic is known as a saturated motor, while a motor having a steep speed characteristic is known as an unsaturated motor. In general, the saturated motor is chosen for application to passenger cars and the unsaturated motor for application to trucks or tractors.

90. General electrical requirements. Vehicle motors are manufactured in various sizes, each of which can be supplied in several electrical ratings. The features of design conform closely to railway motor practice, since the conditions of vehicle service are very severe and quite similar to traction service. The motors are designed with liberal commutator capacity and the best possible commutating characteristics, in order to withstand the extreme overloads encountered. In addition, they should possess high efficiency, ruggedness, durability, and general reliability. They must be capable of operating over a considerable range of voltage.

91. Mechanical features. The magnet frame and the commutator end housing are in general cast integral, the outer surface of the cylindrical frame

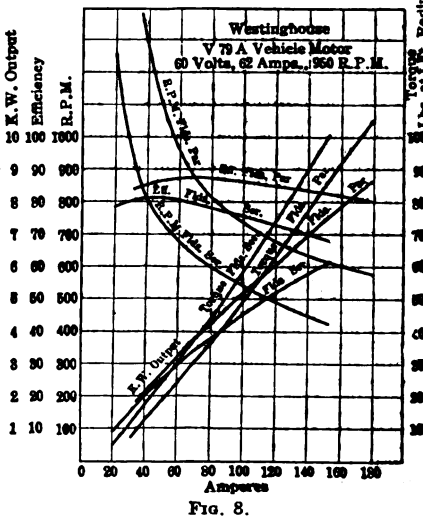


FIG. 8.

usually being machined from end to end. This design lends itself to the application of various forms of suspension brackets. In some designs the magnet frame is made from a rolled steel plate of cylindrical construction having cast-iron, steel, or malleable-iron end housings bolted to each end. The bearing heads of both the commutator and the pinion ends are made of cast iron or bronze and are of the closed type. The armature bearings are of the annular ball type, firmly fastened to the shaft by a retaining nut and protected from dust by a bearing cap. This cap also acts as a retainer for the lubricant. The shaft extension is usually tapered and extends from the pinion end of the motor. The commutators are made of hard-drawn copper with the mica undercut to a depth of approximately $\frac{1}{16}$ in.

The armatures after being wound are baked, dipped in a special dipping varnish and baked a second time. The field coils are impregnated with asphaltum under a vacuum process and after being baked are given a final treatment in dipping varnish. This renders both the armature and field windings practically impervious to moisture. The field coils are arranged in

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two groups, so that they may be connected either in series or in series parallel. Six leads are brought out from the frame, comprising two armature and four field leads, to facilitate connections for the field-control. Two brush arms are in general employed, in order to provide greater accessibility to the brushes. In some designs a shorter overall frame is required, in which case four brush arms are provided, resulting in a more compact design.

92. General motor characteristics. The characteristic curves of torque, speed and current for several types of motors are shown in Figs. 8, 9, 10, 11, and 12, being representative data of two leading makes.

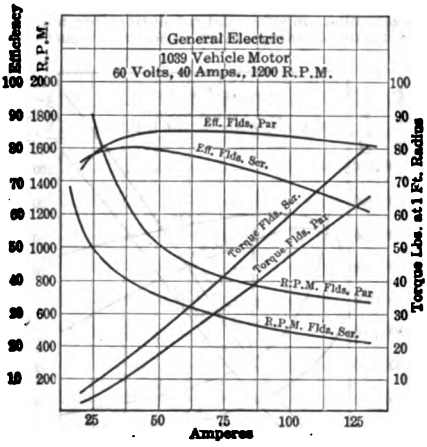


FIG. 9.

93. The performance specification covering vehicle motors may be outlined as follows:

Rating. The normal full-load rating of each motor is based on the specified voltage and amperes. Where series field-coils are arranged for series and parallel connection, the rating is given with field coils connected in parallel.

Speed. The rated speed is based upon the speed of the motor at the end of the specified full-load temperature run. Speeds of individual motors may vary 5 per cent. above or below the rated speed at full load. Approximate speed for loads other than full or rated load are shown on the specified curve.

Efficiency. The efficiencies shown on the specified curve are to be calculated from I^2R losses in the brush contacts and the armature and field windings, based on the measured resistance of these windings at a temperature of 75 deg. cent., and the measured core loss and friction losses, including brush and bearing friction and windage. These losses are to be determined separately for each load at which efficiency is desired. The efficiencies shown on the specified curve are approximate and represent the average of the manufactured product.

Commutation. Each motor shall operate at rated full load with no sparking or burning of the brushes and without blackening of the commutator. Each motor shall operate at any load encountered in normal operation without injurious sparking.

Temperature. After a continuous run (for 4 hours) at the specified voltage and current, no part of the windings shall exceed a temperature of 65 deg. cent. above the surrounding air. Test shall be made on the stand with motor covers on. Temperature shall be measured by thermometer.

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94. S. A. E. motor standards. The practice recommended by the Society of Automotive Engineers in regard to electric vehicle motors is as follows:

Motor voltage. Two classes of motors shall be used for electric vehicles (not including industrial trucks and tractors), the first class designed for 80-volt to 85-volt operation, characteristic curves to be furnished by the manufacturers for each voltage. The second class of motors shall be designed for 60-volt to 66-volt operation, the characteristic curves for each of these voltages to be furnished by the manufacturers.

Motor nameplates. Each motor shall carry a nameplate setting forth: Manufacturer's name and address; whether series, shunt, or compound wound; frame size; volts, amperes, and revolutions per minute, for both the high and the low limits of voltage, given in separate figures.

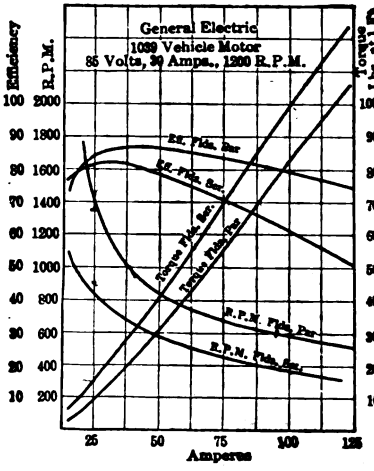


FIG. 10.

95. Motor windings. As the result of the standardization of 40 to 44 cells of lead battery and 60 cells of Edison battery, the motor manufacturers have designed their respective lines of motors so that either of two windings can be provided for each frame. The one, an 80-volt to 85-volt rating, is designed for use with a 40-cell to 44-cell lead battery, and the other, a 60-volt rating, is designed for use with a 60-cell Edison battery. The two windings are so designed that the motor will have the same speed and torque at normal rated load for both voltage ratings. This can be seen by comparison of the curves in Figs. 9 and 10 and Figs. 11 and 12.

96. Standard motor sizes. The standard motors of two well-known manufacturers are listed in the table in Par. 98, showing the ratings and the weights.

97. Choice of number of motors. The choice of one, two, or four motors is dependent upon the type of transmission employed. The single-motor drive is generally favored because of its high efficiency, light weight, and simplicity of control. The two-motor drive gives slightly better performance when the stops per mile are very frequent, due to the elimination of running resistance in the first notches of the controller, but it is doubtful whether this advantage offsets the additional weight and maintenance necessitated by the additional motor.

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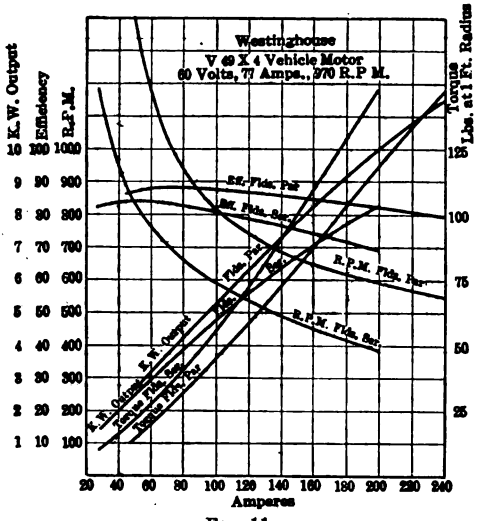


FIG. 11.

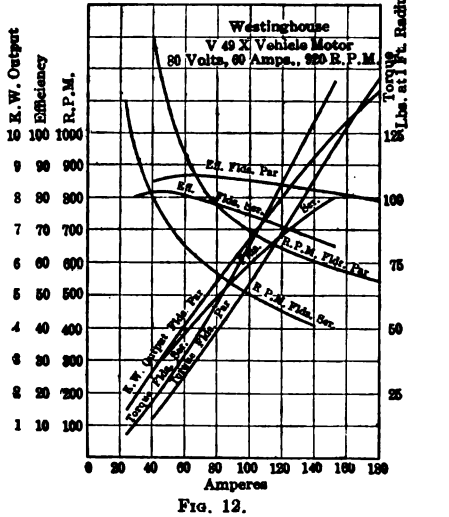


FIG. 12.

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98. Standard Vehicle Motor Ratings
(General Electric Co.)

Type	Volts	Amp.	R.p.m.	Wt. (lb.)	Type	Volts	Amp.	R.p.m.	Wt. (lb.)
GE 1086	24	32	1,900	45	GE 1048	60	40	1,600	265
	36	21	1,800	45		85	30	1,600	265
GE 1083	24	40	1,500	75	GE 1064	48	50	1,500	315
GE 1065	60	17	1,600	130	GE 1039	60	40	1,200	310
	85	12	1,600	130		85	30	1,200	310
GE 1090	24	45	1,200	170	GE 1022	60	60	1,200	425
	24	50	1,500	170		85	40	1,200	425
	32	35	1,500	170	GE 1030	60	70	850	530
	40	35	2,000	170		85	50	850	530
GE 1091	24	65	1,700	200	GE 1027	60	85	900	600
	32	60	1,500	200		85	60	900	600
	48	45	1,700	200	GE 1087	80	120	900	800

(Westinghouse Elec. & Mfg. Co.)

Typr	Volts	Amp.	R.p.m.	Wt. (lb.)	Type	Volts	Amp.	R.p.m.	Wt. (lb.)
V-62-X-4	60	36	1,160	145	V-50-X-4	60	57	1,190	300
V-62-X	80	28	1,160	145	V-50-X	80	43	1,190	300
V-51-X-4	60	44	1,100	190	V-49-X-4	60	77	970	430
V-54-X	80	33	1,090	190	V-49-X	80	60	920	430
V-77-A	80	40	950	250	V-43-X-4	60	120	800	600
V-79-A	60	62	910	280	V-43-X	80	90	840	600

99. Choice of proper size of motor. In applying a motor to a passenger car or truck, it has been found by experience that a motor having a normal current rating equal to the current required to propel the car on hard level, smooth pavement at its rated speed and load capacity will, in general, have sufficient capacity to propel the car under general operating conditions without exceeding the safe temperature limits. The following general expressions can be used to determine the capacity of motor required, or other variable involved:

$$TE = W \times R \text{ (lb.)} \quad (1)$$

$$EI = \frac{TE \times MPH}{0.502 \times e_g \times e_m} \text{ (watts)} \quad (2)$$

$$I = \frac{TE \times MPH}{0.502 \times E \times e_g \times e_m} \text{ (amp.)} \quad (3)$$

Substituting the value of TE from equation (1),

$$I = \frac{W \times R \times MPH}{0.502 \times E \times e_g \times e_m} \text{ (amp.)} \quad (4)$$

also

$$I = \frac{W \times w.h. \times MPH}{E} \text{ (amp.)} \quad (5)$$

$$MPH = \frac{N \times D}{336 \times g.r.} \quad (6)$$

$$T = \frac{TE \times D}{g.r \times 24 \times e_g} \quad (7)$$

$$= \frac{W \times R \times D}{g.r. \times 24 \times e_g} \quad (8)$$

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Where TE = tractive effort required at rims of driving wheels, in lb.
W = gross weight of vehicle in tons.
R = total frictional resistance, in lb. per ton.
E = voltage at motor terminals.
I = current in amperes.
MPH = speed of vehicle in miles per hour.
T = motor torque in lb. at 1 ft. radius.
e_g = efficiency of gearing, assumed usually as 95 per cent. for single reduction and 90 per cent. for double reduction.
e_m = efficiency of motor, usually 85 to 88 per cent., average 86 per cent.
$w.h.$ = watt hours per ton mile
N = speed of motor armature in revolutions per minute.
D = diameter of driving wheels in inches.
$g.r.$ = total speed reduction ratio between motor shaft and driving wheels.

100. The rolling resistance of a wheel is due theoretically to the yielding or indentation of the road, which causes the wheel continually to mount a slight incline. It is also affected by the yielding or deformation of the wheel tread at the point of contact with the road. The resistance is measured by the horizontal force necessary at the axle to lift it over the obstacle or roll it up the incline surface. The rolling resistance varies with the diameter of the wheel, the width and composition of the tire, the construction of the tire, the method of attaching the tire to the wheel rim, the speed, the nature of the road surface, the grade and the spring suspension.

101. The air resistance varies approximately as the square of the speed, but is usually not considered in electric vehicle practice because the speeds are relatively so low that it is negligible.

102. Vehicle resistance is given by the best authorities as having the following values:

Steel-tired wheels on steel rails	6 to 20 lb. per ton
Pneumatic tired wheels on level hard asphalt pavement	15 to 35 lb. per ton
Solid-tired wheels on level hard asphalt pavement	20 to 40 lb. per ton
Steel-tired wheels on average roads, approximately	50 lb. per ton

103. The relative values of vehicle resistance on various level road surfaces, as compared to the value on hard level asphalt, are given in the following table.

Road surface	Relative value of vehicle resistance	Road surface	Relative value of vehicle resistance
Asphalt, hard	1.00	Snow packed	1.3
Macadam	1.15	Snow fairly hard, without grips	1.7
Tarvia	1.14	Snow fairly hard, with grips	1.9
Glazed brick	1.35	Snow, soft	2.1
Wood block	1.1		
Granite block	2.0		

104. The vehicle resistance for a passenger car may be assumed as 20 to 30 lb. per ton for operation on level hard smooth asphalt.

105. The vehicle resistance for electric trucks on level hard smooth asphalt has been found by experience to be approximately as follows:

Capacity of truck, lb.	Pounds per ton	Watthours per ton mile
1,000	40	90
2,000	40	85
4,000	35	80
7,000	30	75
10,000	30	75

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106. Effect of grades. The effect of grades is to increase or decrease the value of the vehicle resistance by 20 lb. per ton for each per cent grade.

107. The energy consumption and power demand of electric vehicles are governed by the gross weight, speed, character of roads, grades and frequency of stops.

VEHICLE CONTROL

108. Two general methods. There are two general methods of control. In the first the battery cells are connected permanently in series and in the other the battery is commutated, that is, the battery cells are divided into two equal groups, which can be connected in parallel or series combination.

109. In the first method (Par. 108) two resistance notches are generally used before the "field-series" notch is reached. Between this position and the "fields-parallel" position an intermediate position is provided in which a resistance is in parallel circuit or shunt with the field coils. This is not absolutely necessary but it is done so that the increase of current or torque from notch to notch is uniform. In some cases another position is provided beyond the normal running or "field-parallel" position in which a resistance is in parallel with the field coils to secure a still higher operating speed. This is what is commonly known as an emergency speed and is usually found only on controllers designed principally for application to passenger cars. The controller is often arranged so that it is necessary for the operator to maintain the handle in this position against the force of a spring tending to turn the handle back to the series-parallel position. A controller of this first general type provides two economical running speeds, one with "fields series" and the other with "fields parallel."

110. The second method affords a slightly better efficiency of operation in that energy is not dissipated through ohmic resistance during acceleration. Formerly this method was highly objectionable because the controllers were not of the continuous-torque type, that is, the circuit was interrupted when the drum was rotated from notch to notch. Furthermore some trouble was encountered because of unequal discharge of the two sections of the battery. Continuous-torque controllers have been developed, which in addition to the foregoing feature have an improved system of battery bridging that obviates the trouble arising from the unbalancing of the two sections of the battery. The bridging is accomplished in the momentary transition from "batteries parallel, field-series," to the position "battery series, field series" by consecutive momentary transition combinations as follows:

(*a*) A resistance is in parallel circuit with a battery section in parallel one group of field circuits open circuited.

(*b*) Battery sections in series, resistance connected between the two sections, fields in series, one group short circuited.

(*c*) Battery sections in series, resistance connected between the two sections, field coils in series.

It will be seen that in the transition both sections of the battery are discharged at equal rates, never becoming unbalanced. With this second method, four economic running speeds are provided as compared with two for the first, these being "fields series" and "fields parallel" connections with the battery sections connected in parallel and in series respectively. In the operation of a vehicle where there are numerous acceleration periods this method results in more economical operation. It also permits of economical operation at low speeds in congested traffic zones.

111. General features. In general controllers should be so designed and built that compactness, ruggedness, ease of operation and accessibility are secured.

112. Drum type. Controllers are usually of the drum type, employing one drum for manipulating the connections for both forward and reverse speeds, or two drums, comprising a main drum for controlling the speed combinations and a reverse drum for reversing the armature circuit. In the latter type the main drum and the reverse drum are interlocked, so that the reverse drum is inoperative while the main drum is in any "on" position, it being necessary to return the main drum to the "off" position before the reverse drum can be operated.

113. Controllers for passenger cars usually have a greater number of speeds forward than those for application to electric trucks, since the opera-

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ing speeds of the passenger car are higher and uniform acceleration is necessary. In some controllers for passenger car service an emergency speed is obtained by shunting a resistance around the parallel fields of the motor (Par 109).

114. The various speed notches on the controller should be indicated positively by action of the star wheel and pawl. In the case of a single-drum type of controller, there should be a considerable break between the first forward and the first reverse positions. In this type the reversing operation is usually effected at the "off" position by a sidewise motion of the handle against the positive pressure of a spring, permitting the handle to be operated in a backward direction from the "off" position in an off-set slot. This arrangement prevents the sudden reversal of the motor by the careless operation of the controller handle by the driver.

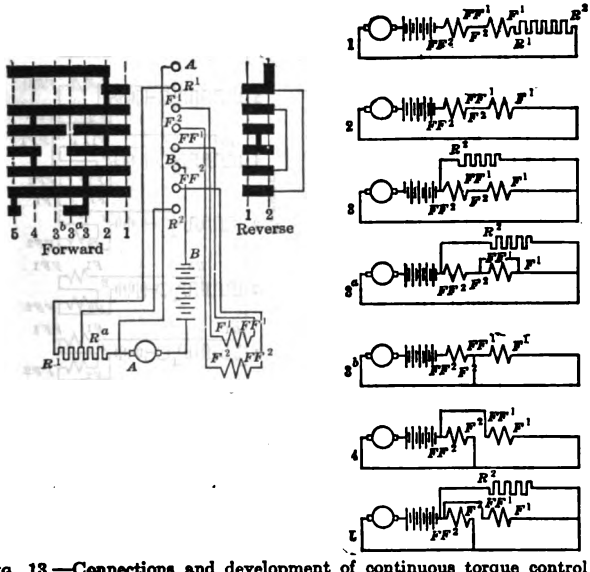


FIG. 13.—Connections and development of continuous torque control for single motor equipment.

115. Angular travel. The angular throw of the handle should be as small as possible, but the peripheral travel of the contact surfaces of the control drum must be great enough to rupture the arcs when the drum is rotated from notch to notch.

116. Drum construction. The drum bases or cylinders are made of wood or of molded material, attached by spiders to the operating shaft. The main drums are operated either by a handle attached directly to the shaft, or through a pinion and sector gear, the latter being fastened to a stub shaft, to which the operating handle is attached. With the latter form of operating mechanism the gear reduction is approximately 3 to 1 so that the distance through which the handle moves is greatly reduced in comparison with that through which the controller drum rotates in moving from notch to notch.

117. Continuous torque operation is a desirable feature of control because it permits the current to flow uninterruptedly while the controller drum is being rotated from notch to notch, forward or reverse, thereby secu

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ing maximum life of contact fingers and plates and smooth efficient acceleration. In the system of control ordinarily used, the interruption of the current will take place only in the transition from the series to the series-parallel field connection.

118. Typical controller connections embodying the continuous-torque feature are illustrated in Fig. 13. The continuous torque feature is effected as follows: On the third position the motor fields are in series and shunted with the resistance R^2. As the controller drum is rotated between the positions 3 and 4, a short-circuit is introduced at 3^a around one set of fields. Referring to the drum development, it will be noted that this is caused by the contact finger which bridges across the gap on the contact F^2, thus momentarily connecting F^1 and FF^2. In the next momentary transition 3^b, the shunt R^2 is removed, and the field connection FF^1 is opened; the

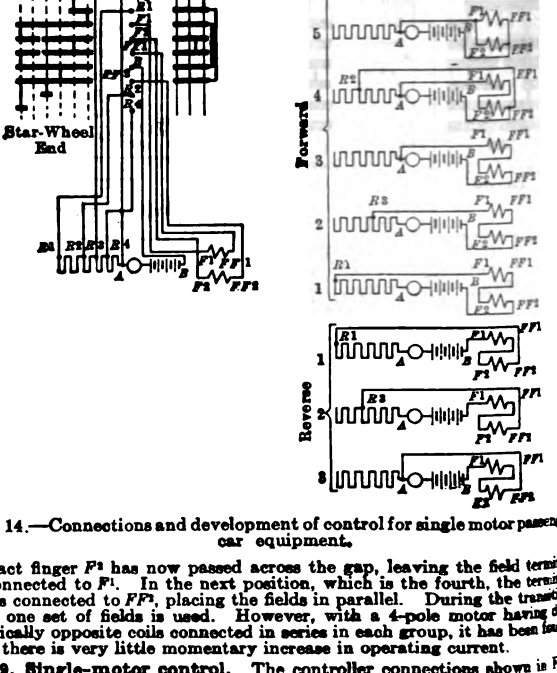


FIG. 14.—Connections and development of control for single motor passenger car equipment.

contact finger F^2 has now passed across the gap, leaving the field terminal F^2 connected to F^1. In the next position, which is the fourth, the terminal FF^1 is connected to FF^2, placing the fields in parallel. During the transition only one set of fields is used. However, with a 4-pole motor having diametrically opposite coils connected in series in each group, it has been found that there is very little momentary increase in operating current.

119. Single-motor control. The controller connections shown in Fig. 13 are representative of those for single-motor trucks, while those in Fig. 14 are representative of single-motor passenger cars.

120. Controllers for industrial trucks and tractors are of the drum type and are usually arranged for three speeds forward and reverse. The first speed is obtained by connecting the two sections of the motor field in series with a resistance, the second speed by short-circuiting the resistor and the third speed by paralleling the two sections of the motor field.

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principal function of the three speed points is to start the truck gently, as very little actual speed control is required. In tractor equipments the resistor point is useful, however, because slow speed is desired when coupling trailers.

121. Double-motor control. With double-motor equipments the general scheme of control is the same as for single-motor equipments, a series-parallel commutation of the motors being usually employed, with series resistance for starting and intermediate steps. At starting, the motors are connected in series with all resistance in circuit.

122. The control resistors are usually either of cast iron or cast alloy. In some cases, to prevent rusting, the grids are copper plated and treated with aluminum paint. The grids are usually assembled on tie rods, mica insulated and held between two pressed or punched steel end-frames.

123. A main switch is usually provided, so that the controller can be isolated from the battery circuit when the battery is on charge.

STORAGE BATTERIES

124. General. The subject of storage batteries as a whole is treated in Section 20. The following discussion relates exclusively to storage batteries in vehicle service and is intended to supplement the subject matter of Section 20.

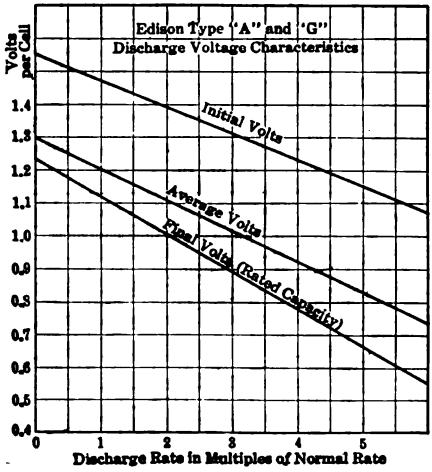


FIG. 15.

125. Three types of batteries in general use on electric vehicles are the Edison, the Iron Clad Exide and the Philadelphia Diamond Grid types *WMT* and *WTXI*. The Philadelphia type *WTXI* is of the thin-plate type and recommended only for passenger car service.

126. Principal characteristics of the Edison battery are embodied in the table in Par. **129**, the Iron Clad Exide in Par. **130**, the Philadelphia type *WMT* in Par. **131** and the Philadelphia type *WTXI* in Par. **132**.

127. The battery discharge in vehicle service, in all applications, occurs at varying rates and is accompanied by intermittent periods of rest. The total elapsed time of discharge is ordinarily eight hours or more. The reduction in capacity due to high discharge rates largely disappears when the rate

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are intermittent. Therefore, the normal discharge-rate capacity specified by the manufacturers will be available, provided the total elapsed time during which the discharge takes place is not less than 6 hr.

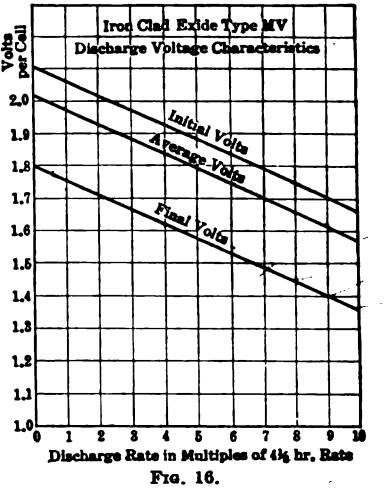


FIG. 16.

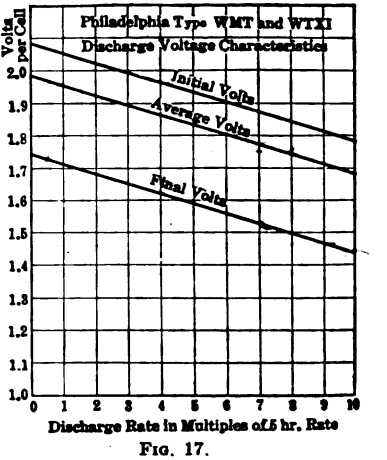


FIG. 17.

128. The discharge voltage characteristics at various multiples of the normal discharge rate are given in Fig. 15 for the Edison battery, Fig. 16 for the Iron Clad Exide Battery and Fig. 17 for the Philadelphia types *WMT* and *WTXI*.

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129. Data on Edison Type "A" and "G" Cells
(Applying to Individual Cells)

Type of cell	A4	A5	A6	A8	A10	A12	G4	G6	G7	G9	G11	G14	G18
Amp.-hr. capacity (rated)	150	187.5	225	300	375	450	100	150	175	225	275	350	450
Kw.-hr. capacity (rated)	0.180	0.225	0.270	0.360	0.450	0.540	0.120	0.180	0.210	0.270	0.330	0.420	0.540
Discharge rate:													
(*a*) Normal, amp.	30	37.5	45	60	75	90	30	45	52.5	67.5	82.5	105	135
(*b*) Max. for intermittent discharge, amp.	180	225	270	360	450	540	180	270	315	405	495	630	810
Normal charging rate, amp.	30	37.5	45	60	75	90	30	45	52.5	67.5	82.5	105	135
Dimensions, bottomless trays (in.):													
(*a*) Width	$6\frac{1}{8}$	$6\frac{1}{8}$	$6\frac{1}{8}$	$6\frac{1}{8}$	$7\frac{3}{4}$	9	$6\frac{1}{8}$	$6\frac{1}{8}$	$6\frac{1}{8}$	$6\frac{1}{8}$	$6\frac{1}{8}$	$7\frac{3}{4}$	$9\frac{5}{8}$
(*b*) Height overall—filler cap closed	$14\frac{3}{8}$	$14\frac{3}{8}$	$14\frac{3}{8}$	$14\frac{1}{4}$	$14\frac{3}{4}$	$15\frac{1}{2}$	$14\frac{3}{8}$	$14\frac{3}{8}$	$14\frac{3}{8}$	$14\frac{3}{8}$	$14\frac{1}{4}$	$14\frac{3}{4}$	$15\frac{1}{2}$
Height overall—filler cap open	16	16	16	$16\frac{3}{8}$	$16\frac{3}{8}$	17	16	16	16	16	$16\frac{3}{8}$	$16\frac{3}{8}$	17
(*c*) Length: 1-cell tray	$4\frac{5}{8}$	$5\frac{1}{2}$	$5\frac{3}{4}$	$7\frac{1}{2}$	$7\frac{1}{2}$	$7\frac{1}{2}$	$4\frac{1}{2}$	$4\frac{3}{4}$	$5\frac{1}{4}$	6	$7\frac{1}{2}$	$7\frac{1}{2}$	$7\frac{1}{2}$
2-cell tray	$7\frac{3}{4}$	9	10	$12\frac{7}{8}$	$13\frac{1}{2}$	$13\frac{1}{2}$	$6\frac{3}{4}$	8	9	$10\frac{3}{8}$	$12\frac{7}{8}$	$13\frac{1}{2}$	$13\frac{1}{2}$
3-cell tray	$10\frac{7}{8}$	$12\frac{3}{4}$	$14\frac{1}{4}$	$18\frac{3}{8}$	$19\frac{1}{2}$	$19\frac{1}{2}$	$9\frac{3}{8}$	$11\frac{1}{4}$	$12\frac{3}{4}$	$14\frac{7}{8}$	$18\frac{3}{8}$	$19\frac{1}{2}$	$19\frac{1}{2}$
4-cell tray	14	$16\frac{3}{8}$	$18\frac{1}{2}$	$24\frac{1}{8}$	$25\frac{7}{8}$	$25\frac{7}{8}$	$12\frac{1}{8}$	$14\frac{7}{8}$	$16\frac{3}{8}$	$19\frac{1}{8}$	$24\frac{1}{4}$	$25\frac{7}{8}$	$25\frac{7}{8}$
5-cell tray	$17\frac{1}{8}$	20	$22\frac{3}{4}$	$29\frac{3}{4}$	$32\frac{1}{4}$	$32\frac{1}{4}$	15	$18\frac{1}{8}$	20	$24\frac{1}{4}$	$29\frac{3}{4}$	$32\frac{1}{4}$	$32\frac{1}{4}$
6-cell tray	$20\frac{1}{4}$	$23\frac{5}{8}$	$27\frac{1}{4}$	36	.....	.....	$17\frac{5}{8}$	$21\frac{3}{8}$	$23\frac{5}{8}$	$28\frac{1}{2}$	36	.....	.....
7-cell tray	$23\frac{1}{4}$	$28\frac{1}{2}$	32	$41\frac{5}{8}$	.....	.....	$20\frac{1}{2}$	25	$28\frac{1}{2}$	$33\frac{3}{8}$	$41\frac{5}{8}$	.....	.....
8-cell tray	$27\frac{1}{2}$	$32\frac{1}{4}$	$36\frac{1}{4}$	$47\frac{1}{8}$	.....	.....	$23\frac{1}{4}$	$28\frac{1}{4}$	$32\frac{1}{4}$	$37\frac{3}{4}$	$47\frac{1}{8}$	.....	.....
9-cell tray	$30\frac{3}{8}$	36	$41\frac{1}{8}$	$53\frac{3}{8}$	.....	.....	$25\frac{7}{8}$	$31\frac{1}{2}$	36	$42\frac{1}{4}$	$53\frac{3}{8}$	.....	.....
10-cell tray	$33\frac{1}{4}$	$40\frac{1}{2}$	$45\frac{1}{8}$	.....	.....	.....	$28\frac{7}{8}$	$35\frac{1}{2}$	$40\frac{1}{2}$	47	.....	.....	.....
11-cell tray	$36\frac{3}{8}$	$43\frac{7}{8}$	.....	.....	.....	.....	$31\frac{1}{8}$	$38\frac{3}{8}$	$43\frac{7}{8}$	.....	.....	.....	.....
12-cell tray	$40\frac{5}{8}$	.....	.....	.....	.....	.....	$34\frac{1}{8}$	$41\frac{5}{8}$	.....	.....	.....	.....	.....
Weight in lb.:													
(*a*) Solution	3.1	3.6	4.1	6.1	7.7	9.4	2.4	3.4	4.0	4.7	5.8	7.3	10.2
(*b*) Complete cell	13.8	16.7	19.4	26.8	33.3	40.6	10.9	15.1	17.4	21.1	27.3	34.0	44.5
(*c*) Complete cell, including tray	14.9	17.5	20.8	29.0	36.2	43.9	13.0	16.8	18.2	23.0	29.6	36.9	47.8

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are intermittent. Therefore, the normal discharge by the manufacturers will be available, provided the which the discharge takes place is not less than 6

180. Data on Iron-clad Exide A.
(Applying to Individual Ce.

Number of plates	7	9	11	13	15	17		
Amp.-hr. capacity (6-hr. rate)	102	136	170	204	238	272	30	
Kw.-hr. capacity (6-hr. rate)	0.201	0.268	0.335	0.402	0.469	0.536	0.6	
Discharge rate (4½-hr. rate), amp.	21	28	35	42	49	56	63	
Normal charging rate:								
(a) Starting, amp.	19	24	30	35	40	45	51	
(b) Finishing, amp.	8	10	12	14	16	18	20	
Cell dimensions (not including tray):								
(a) Outside length (in.)	2⅛	3⅛	4⅛	5⅛	6⅛	6⅛	7⅛	6
(b) Outside width (in.)	6¼	6¼	6¼	6¼	6¼	6¼	6¼	6¼
(c) Overall height (in.)	15	15	15	15	15¼	15¼	15¼	15¼
Weight in pounds:								
(a) Electrolyte	4½	5½	6½	8	9½	10½	11½	13
(b) Complete cell	23½	30	36½	43½	49½	57½	63½	70
(c) Complete cell, including tray	27	35	42	49	57	66	73	81

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131. Data on Philadelphia Type V

(Applying to Individual Cells)

Number of plates	9	11	13	15	17	19						
Amp.-hr. capacity (6-hr. rate)	124	155	186	217	248	279	5					96
Kw.-hr. capacity (6-hr. rate)	0.244	0.305	0.366	0.428	0.489	0.550	0.					0.977
Discharge rates:												
(*a*) 6-hr. rate, amp	20.7	25.8	31	36.2	41.3	46.5	51.7					82.7
(*b*) 5-hr. rate, amp	24	30	36	42	48	54	60					96
Normal charging rates:												
(*a*) Starting, amp	24	30	36	42	48	54	60				84	96
(*b*) Finishing, amp	6	7.5	9	10.5	12	13.5	15	16.			21	24
Cell* dimensions (not including tray):												
(*a*) Outside length (in.)	$3\frac{1}{16}$	$3\frac{9}{16}$	$4\frac{5}{16}$	$4\frac{7}{8}$	$5\frac{9}{16}$	$6\frac{1}{2}$	$6\frac{7}{8}$	$7\frac{1}{2}$		$8\frac{3}{4}$	$9\frac{3}{4}$	$10\frac{5}{8}$
(*b*) Outside width (in.)	$6\frac{1}{16}$	$6\frac{1}{16}$	$6\frac{1}{16}$	$6\frac{1}{16}$	$6\frac{1}{16}$	$6\frac{1}{4}$	$6\frac{1}{4}$	$6\frac{1}{4}$		$6\frac{1}{4}$	$6\frac{1}{4}$	$6\frac{1}{4}$
(*c*) Overall height (in.)	$14\frac{13}{16}$	$14\frac{13}{16}$	$14\frac{13}{16}$	$14\frac{13}{16}$	$14\frac{13}{16}$	15	15	15		15	15	15
Weight in lb.:												
(*a*) Electrolyte	5.0	6.1	7.1	8.3	9.3	10.5	11.5	12.7	14.0	15.2	16.2	18.6
(*b*) Complete cell	27.5	32.5	37.5	42.5	47.5	53.0	58.0	63.5	70.0	76.0	82.0	94.0
(*c*) Complete cell, including tray	30.8	35.8	41.3	46.8	52.3	58.3	63.8	69.9	77.0	83.6	90.2	103.4

* Dimensions embody S.A.E. standard jars having $\frac{5}{32}$-in. walls for 9 to 17 plates inclusive, and $\frac{1}{16}$-in. walls for 19 to 33 plates all with $2\frac{1}{4}$-in. ribs. Height specified is from bottom of jar to highest projecting point at top of cell.

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132. Data on Philadelphia Type WTXI Cells

(Applying to Individual Cells)

Number of plates	9	11	13	15	17	19	21
Amp.-hr. capacity:							
(*a*) 6-hr. rate	102	127	153	178	204	229	255
(*b*) 5-hr. rate	98	122	147	171	196	220	245
Kw.-hr. capacity:							
(*a*) 6-hr. rate	0.201	0.251	0.301	0.352	0.402	0.452	0.502
(*b*) 5-hr. rate	0.191	0.238	0.286	0.334	0.382	0.430	0.478
Discharge rates:							
(*a*) 6-hr. rate, amp	17.0	21.2	25.5	29.7	34.0	38.2	42.5
(*b*) 5-hr. rate, amp	19.6	24.5	29.4	34.3	39.2	44.1	49.0
Normal charging rates:							
(*a*) Starting, amp	17	22	25	30	34	38	43
(*b*) Finishing, amp	4	5	6	8	9	10	12
Cell* dimensions (not including tray):							
(*a*) Outside length (in.)	$2\frac{1}{16}$	$2\frac{11}{16}$	$3\frac{1}{16}$	$3\frac{11}{16}$	$4\frac{1}{16}$	$4\frac{11}{16}$	$5\frac{1}{16}$
(*b*) Outside width (in.)	$6\frac{1}{8}$	$6\frac{1}{8}$	$6\frac{1}{8}$	$6\frac{1}{8}$	$6\frac{1}{8}$	$6\frac{1}{8}$	$6\frac{1}{8}$
(*c*) Overall height (in.)	$14\frac{1}{2}$	$14\frac{1}{2}$	$14\frac{1}{2}$	$14\frac{1}{2}$	$14\frac{1}{2}$	$14\frac{1}{2}$	$14\frac{1}{2}$
Weight in lb.:							
(*a*) Electrolyte	3.25	4.25	5.25	6.0	6.75	7.75	8.75
(*b*) Complete cell	17.25	21.25	25.25	29.0	33.0	37.0	41.0
(*c*) Complete cell, including tray	19.0	23.4	27.8	31.9	36.3	40.7	45.1

* Dimensions embody S.A.E. standard jars having $\frac{1}{4}$-in. walls and $2\frac{1}{2}$-in. ribs. Height specified is from bottom of jar to highest projecting point at top of cell.

BATTERY CHARGING

133. General Principle. To charge a battery fully after discharge it necessary to pass through the cells in a direction opposite to that of dis-harge an amount of current equivalent in ampere-hours to that taken out discharge, plus an excess to compensate for losses.

134. Permissible charging rate of Edison batteries. In the case of ie Edison battery the cells may be charged at any rate which does not cause ie temperature of the solution in the cells near the center of the battery rise above 115 deg. fahr.

135. Permissible charging rate of lead batteries. In the case of the ead battery, if the charging rate is not excessive, practically all the current utilised for charging the plates. If the charging rate is increased, a point reached where gassing begins, caused by bubbles of oxygen and hydrogen ormed at the surface of the plates by decomposition of water in the electro-yte. This gassing increases with further increase in the charging rate. he excessive portion of the current which causes gassing produces no useful ffect in charging the plates and is wasted. These high charging rates, which produce violent gassing, are not only wasteful of electric energy but tend to dislodge the active material from the plates, producing an excessive temperature rise, and materially shortening of the life of the plates. In general, any charging rate is permissible which does not produce excessive gassing or a cell temperature exceeding 110 deg. fahr.

136. Factors which affect gassing. The value of the charging current at which appreciable gassing begins in lead cells depend upon several factors such as the state of charge, temperature, specific gravity of electrolyte, type of plate, etc., but the principal factor is the state of charge of the battery. When the battery is fully charged any rate of charge however small will produce gassing, but the rate may be reduced to such a low value that, unless abnormally prolonged, the small amount of gassing which results is practically harmless. This safe rate is called the "finishing rate." During the early stage of the charge, the charging rate may be several times the finishing rate without producing violent gassing and the more completely the battery is discharged the higher may be the charging rate without causing excessive gassing.

137. Method of charging to prevent gassing. It has been found that if the charging rate throughout the charge of a lead battery is constantly adjusted to a value equal in amperes to the number of ampere hours out of the battery at any instant, violent gassing and excessive rise of temperature will be avoided.

138. Three common methods of charging. There are three common methods of charging batteries, as follows:

(1) The constant-current method.
(2) The constant-potential method.
(3) The modified constant-potential method.

139. The constant-current method. In the case of Edison cells this method involves the passing of a uni-directional current through the battery at the normal rate throughout the charge, without change. With lead cells the starting rate is maintained until the charge has progressed sufficiently to cause slight gassing or until the voltage has risen to a value of approximately 2.5 volts per cell; at this point the current is reduced to the finishing rate by manipulating the field rheostat of the generator or increasing the resistance in the charging rheostat. In order to maintain the proper rate it is necessary, at periodic intervals during the charge, to adjust either the generator field rheostat or the charging rheostat. The constant-current method is inherently a non-automatic method, since an adjustment of rheostat is necessary to maintain the constant rate.

140. Constant-current method for Edison batteries. The constant-current method has been recommended as best suited for charging Edison batteries, because it is more flexible and more easily handled by the operator.

141. The constant-potential method of charging is the method wherein the battery is connected, without a series rheostat, to a constant supply voltage, the particular value of which depends upon the battery to be charged. For a lead battery, the supply voltage should be approximately 2.3 to 2.4 volts per cell and for an Edison battery approximately 1.7 volts

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per cell. This method of charging, however, involves a considerable increase in the initial charging rate, which in many cases would necessitate excessive carrying capacity in charging apparatus and conductors. It requires considerable care in adjusting the bus voltage to meet the changes in temperature at different seasons and the charging rate may be subject to undesirable variations with slight fluctuations in bus voltage.

142. Constant-potential method for Edison batteries. This method may be used for charging Edison batteries under certain specific conditions, which should be determined by competent engineers. Only batteries in approximately the same state of discharge can be charged from a bus-layout which has been designed for this specific condition.

143. Advantages of constant-potential method. This method of charging has some advantages over the other methods and also some inherent disadvantages. It is the most efficient method, there being no resistor in the charging circuit and consequently no rheostatic losses. The control equipment is the simplest and the battery is charged automatically, the attention of an attendent being unnecessary.

144. Automatic charging. Any number of batteries up to the capacity of the supply circuit may be charged from the supply source. Automatic termination of the charge can be secured by the application of an ampere-hour meter and a magnetic contactor for each individual circuit. It is also possible, by the proper design of control equipment, to charge any number of batteries from a motor-generator set of proper capacity and secure full automatic operation of the entire system. A failure of the motor supply voltage at any time during the charging period will cause the batteries to be disconnected individually and upon the reestablishment of the supply voltage the motor-generator set will be automatically started and the charging of the various batteries automatically resumed. As the batteries become charged, each will be automatically disconnected from the circuit and the disconnection of the last battery will cause the motor generator set to be shut down.

145. Disadvantages of constant-potential method. The high initial charging current necessitates larger capacity of generating and control equipment. A small fluctuation in the supply voltage will affect the charging rate very materially, which makes it necessary to maintain the generator or line voltage at the specific required intensity throughout the charging period. If the supply voltage is only slightly in excess of that required, in charging a lead battery, counter-e.m.f. cells may be connected in series with the battery to reduce the voltage to the proper value. Counter-e.m.f. cells produce an opposing voltage of approximately 3 volts per cell. A resistor in series with the battery will not secure the same results as counter-e.m.f. cells.

146. The modified constant-potential method is the simplest of automatic charging systems, to which, fortunately, the characteristics of the lead storage battery are ideally adapted. Any method that involves manual adjustment introduces additional expense as well as a human element, which is often difficult to control; therefore the automatic charging of vehicle batteries has great advantages. This system consists of either a constant-voltage direct-current bus with a suitable fixed resistance in each charging circuit, or an individual charging machine for each circuit with a drooping characteristic equivalent to that obtainable with the fixed resistance. In either case an ampere-hour meter is arranged to disconnect the battery from the charging circuit upon completion of the charge.

147. Characteristics of modified constant-potential method. This method produces a comparatively high rate of charge at the beginning, which is gradually and automatically tapered as the charge progresses so as never to exceed a safe value. Therefore it is necessary to determine only the proper values for the constant bus-voltage and the fixed resistance to produce the results desired, namely: (1) To complete the charge within the time available; (2) in the case of lead batteries, to end the charge at the finishing rate or less; (3) to avoid a charging current in excess of the capacity of the charging source or the charging circuits.

148. Length of charging period. In fixing the time for completing the charge (Par. 147), advantage should be taken of all the time available, as this will result in lower charging rates, smaller capacities for charging

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apparatus and circuits and lower cell temperatures. The shorter the time available, the higher will be the initial charging rate.

149. Application of modified constant-potential method to lead batteries. In the case of a lead battery, any combination of constant bus-voltage of not less than 2.4 volts per cell and a fixed resistance which will complete the charge at or below the finishing rate will produce safe charging rates throughout the entire charge.

150. Application of modified constant-potential method to Edison batteries. With Edison batteries the time required for a full charge by this method is the same as that required by the constant current method. The bus voltage should not be less than 1.8 volts per cell.

151. Voltage of charging bus. If the bus voltage is subject to sustained variations, it s necessary with lead cells that the conditions be such that the finishing rate of charge will not be exceeded when the bus voltage is at its maximum value, and yet that the charge be completed in the available time, which will depend on the average bus voltage. For any given number of cells, the higher the bus voltage the greater will be the loss in the resistance and therefore the lower will be the efficiency; also, the longer will be the time required to complete the charge of lead cells without exceeding the finishing rate at the end. On the other hand, if the bus voltage is but little in excess of that of the battery, the charging current will become more or less unstable and subject to considerable variation with variations of battery temperature or slight changes in the bus voltage.

152. Best value of bus voltage per cell. For lead cells, when the time available for charging is limited or efficiency is of considerable importance, a bus voltage equal to approximately 2.6 volts per cell will be found generally satisfactory and is recommended. The initial charging current will have several times the value of the finishing rate and will taper off as the charge progresses until it drops to, or below, the finishing rate at the end of the charge.

153. Effect of high-bus voltage and resistance. As the bus voltage and resistance are increased, the number of cells remaining the same, the charging current becomes more nearly constant throughout the charge, thus approaching the constant-current method.

154. Bus voltages lower than 2.6 volts per cell, modified constant-potential method may be used with corresponding reduction in the fixed resistance until the bus voltage is reduced to 2.3 to 2.4 volts per cell, with no resistance in circuit except that of the charging leads.

155. Best length of charging period. A charging period of approximately 12 hr. is required to charge a lead battery when the line voltage is 2.9 volts per cell. When the voltage exceeds this value the charging period will be increased and therefore the time available will probably be the limiting factor, if efficiency is not considered. The disadvantage of a very long charging period under high voltage conditions can be practically obviated by the use of control equipment for the purpose of inserting additional resistance in the charging circuit to reduce the current to the finishing rate. In the case of Edison cells the flatter the current-time curve produced by the higher supply voltage per cell the more desirable the charging characteristics will become, but the accompanying decrease in efficiency will probably be the limiting factor.

156. Modified constant-potential charging is the more desirable of the two non-variable voltage methods for either lead or Edison batteries. It embodies all the features of automatic charging in the constant-potential system and reduces the required capacity of the charging apparatus and the conductors. The charging resistors may be mounted either on the charging sections and wired to the face plates, in order to secure close current adjustment at the start of the charge, or they may be mounted apart from the switchboard. Taps should be provided on the resistors for close adjustment when mounted separately.

157. Equalizing charge. It is desirable occasionally to give a lead battery an equalizing charge by prolonging the ordinary charge until it is quite certain that all the cells and all the plates in each cell are fully charged. It has been customary to do this at various rates below the finishing rate, down to one-half, as a precaution against excessive temperatures. However,

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if it is not practical to provide means for reducing the rate, the finishing rate may be used for the equalizing charge, provided the charge is interrupted when necessary to prevent the temperature from exceeding safe limits.

158. Boosting charge. Any battery may be boosted at high charging rates during brief periods of idleness, thereby materially adding to the charge, provided the temperature of the solution in cells near the center of the battery does not exceed 110 to 115 deg. fahr. The following figures may be used under average conditions for Edison batteries, but values that will not cause excessive heating must be determined in each case by experience: Five minutes at five times normal rate; 15 minutes at four times normal rate; 30 minutes at three times normal rate; 60 minutes at two times normal rate.

Frothing at the filler opening is an indication that the boosting has been carried too far (if the solution is at the proper height) and the high rate should be discontinued at once.

Lead-battery boosting rates may be determined by the following equation:

$$\text{Rate} = \frac{\text{ampere-hours discharged from battery}}{1 + (\text{time in hours available for boosting})}$$

The charging rate in amperes multiplied by the time in hours and by 90 per cent. will give the total ampere-hour capacity which can be added in this manner to the normal or rated ampere-hour capacity, their sum being the total available ampere-hour capacity during operation.

159. Automatic termination of charge can be most satisfactorily obtained by the use of an ampere-hour meter in the battery circuit in conjunction with a shunt-trip circuit breaker or magnetic contactor in the charging circuit, connected in such relationship that when the ampere-hour meter needle is returned to the zero position at the completion of the charge the circuit is completed through the operating coils of the circuit breaker or contactor in a manner such as to cause the device to trip, disconnecting the battery from the supply circuit. A shunt-trip circuit breaker or magnetic contactor has auxiliary contacts which open the tripping circuit when the breaker or contactor functions, thereby avoiding arcing at the ampere-hour meter contacts. The circuit breaker may be located either on the vehicle or on the charging panel and the magnetic contactor is usually located on the charging panel; in the last two cases a third conductor between the battery and the charging panel will be required to complete the tripping circuit. A three-point charging plug and receptacle are available in which the third point is designed for completing the connections of the trip circuit of the ampere-hour meter.

BATTERY CHARGING EQUIPMENT

160. The choice of charging equipment is determined by the conditions as to the source of energy, which may be classified as follows:

I. Direct-current constant-voltage source:
1. Use existing supply circuit if the voltage is suitable.
2. Reduce to suitable voltage by:
   (*a*) Counter-e.m.f. cells for charging lead cells
   (*b*) Balancer set
   (*c*) Motor generator

II. Alternating-current constant-voltage source:
1. Convert to direct current at suitable voltage by:
   (*a*) Motor-generator set.
   (*b*) Synchronous converter.
   (*c*) Mercury-arc rectifier.
   (*d*) Rectifier of Tungar type.

III. Special cases:
   (*a*) Charging for limited time from high-voltage direct-current source with ampere-hour meter control.
   (*b*) Single battery charged from motor-generator or other converting apparatus with drooping characteristics.
   (*c*) Several batteries charged in series from high-voltage bus.

161. Preference for direct-current source. When a direct-current source of energy is available it should be used if practicable. This will obviate the investment required for transforming apparatus and will often dispense with attendants who would be required if rotating machinery were installed.

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162. Reduction of direct-current supply voltage. If it is necessary to reduce the voltage of the existing direct-current supply circuit, this may be accomplished in a number of ways, depending on conditions, as briefly described in Par. 163 to 168.

163. Counter-electro-motive-force cells may be used for charging lead cells if the required voltage reduction is not more than 12 per cent. of the bus voltage. These cells are similar to storage-battery cells (in glass jars or lead-lined tanks), except that the plates have no capacity for discharge. The function of the counter-e.m.f. cell is to absorb a portion of the line voltage and thereby adjust the voltage impressed on the battery terminals. In counter-e.m.f. cells the voltage drop is nearly constant, whereas in a resistor the voltage drop is directly proportional to the current. By the use of the counter-e.m.f. cells, the characteristics of the modified constant-potential method may be secured with a bus voltage somewhat higher than normal and without manual adjustment during charge, whereas if an ordinary rheostat is used, adjustments must be made from time to time to secure equivalent results.

164. The voltage absorbed by a counter-e.m.f. cell varies from 2.3 volts at low current to 3 volts at high current. For continuous service, the current flowing through a counter-e.m.f. cell should be limited to the 3-hr. rate of the corresponding storage cell, but higher rates than this, up to the 1-hr. rate, may be used for short periods or for the initial stage of a tapering charge lasting 8 hr. or less.

165. Auxiliary bus derived from counter-e.m.f. cells. These cells may also be used to provide a second constant-voltage bus, at lower voltage than the main bus, for charging batteries of fewer cells.

166. Use of balancer sets. A balancer set may be used if the bus voltage is approximately twice the value required for charging. This equipment is comprised of two identical direct-current machines mounted on a common shaft and electrically connected in series across the main bus, thus providing a three-wire system, each side of which comprises a suitable source of supply for the modified constant-potential system. If the line voltage is slightly more than twice the value suitable for lead cells, the balancer set can be used in conjunction with counter-e.m.f. cells.

167. Capacity of balancer sets. Where a charging source of double the desired voltage is already available and of ample capacity for all future requirements, a balancer set of sufficient capacity for the maximum demand of the largest single battery will be satisfactory for any number of additional batteries comprised of the same number of cells. The balancer set is required to handle only the unbalanced load, which is the difference in load on the two sides of the three-wire circuit; this difference need never be greater than the maximum demand of the largest battery.

168. A direct-current motor-generator set should be installed if the direct-current bus voltage is either too low or too high and not suitable for a balancer set. This equipment consists merely of a direct-current generator direct-connected to a direct-current motor, with a common bed-plate; belted sets, while practicable, require more room and are more expensive to maintain.

169. Alternating-current motor-generator set for charging Edison batteries. This type of installation for charging an Edison battery from an alternating-current source requires a motor-generator set and a single-circuit automatic control panel. A differential-wound generator has characteristics which make it suitable for charging an Edison battery automatically, inasmuch as it is practically a constant-current machine and maintains a constant charging rate throughout the charge. An individual generator is required for each battery. If automatic termination of the charge is desired, a magnetic contactor and ampere-hour meter must be provided in the control circuit of each battery. This equipment will require no attention after the charge is started. The control equipment can be so designed that it will disconnect the battery from the generator upon completion of the charge and also disconnect the motor from the main supply circuit.

170. Alternating-current motor-generator set for charging lead batteries. Similar equipment (Par. 169) can be used for charging lead cells automatically, by providing the proper control equipment and an

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ampere-hour meter having an additional or intermediate contact. This intermediate contact is arranged to connect an additional resistance into the shunt-field circuit for the purpose of reducing the charging current to the finishing rate when the charge has reached a point within approximately 20 per cent. of completion. In the case of lead batteries the expense of supplying an individual generator and control panel for each battery is not warranted, because they are so well adapted to the modified constant-potential charging method.

171. Charging equipment for commercial trucks. An installation serving two or more commercial trucks will require a motor-generator set, with a generator control section and one charging section per truck. An installation serving two industrial trucks may be equipped with two individual motor-generator sets with automatic control panels, with capacity for one battery each, or with one motor-generator set for both batteries, with generator control panel embodying two charging circuits. An installation serving three trucks or more will require a motor-generator set, with automatic control panel providing one charging section per truck.

172. Charging equipment for passenger cars. For private passenger cars where there is one car in a private garage a mercury rectifier, a Tungar type of rectifier, or a motor-generator set and automatic control panel will be satisfactory. Where there are two or more passenger cars in a public garage a motor-generator set and generator control panel with one charging section for each battery to be charged (at the same time), and also one or two mercury-arc rectifiers for light load conditions, should be satisfactory.

173. Quick charge from high-voltage bus. It will be noted that as the bus voltage increases the minimum time for completing the charge of a lead battery through a fixed resistance, without exceeding the finishing rate, becomes longer. If it is desired to hasten this charge, it can be accomplished without abandoning the automatic feature by using an ampere-hour meter with an extra auxiliary contact and two fixed resistances in parallel in the charging circuit. The charge is started at a high rate through the two resistances and when the charge is partly completed the extra auxiliary contact on the ampere-hour meter open an automatic switch and cut out one of the resistances, after which the charge is continued at a reduced rate through the remaining resistance until completion, when the charge is finally terminated by the other auxiliary contacts on the meter.

174. The extra auxiliary contact on the ampere-hour meter is located at a distance from the zero point equal to 20 per cent. of the total dial range of the meter and is designed so that when the hand of the meter passes it on discharge it closes the contact, and it remains closed until the meter hand opens it when passing in the opposite direction during charge. When connections are made for the charge, this contact being closed, the automatic reclosing breaker which controls the second resistance also closes and the charge continues at the high rate until at the proper time the meter opens the contact and thereupon the breaker opens, thus reducing the rate. This device, while somewhat more complicated than the shunt-trip breaker, offers more complete protection for the reason that if any trouble develops in the extra contact or in its circuit the automatic breaker immediately opens, or fails to close, and thereby prevents excessive charging rates during latter part of the charge.

175. Adaptability of meter to different sizes of battery. It is necessary to use one size of ampere-hour meters for as many as four different sizes of battery, so that it is commercially impracticable to have the extra auxiliary contact on the meter adjustable for each of these battery sizes. The location chosen, at 20 per cent. of the dial range, gives full production under the most severe conditions, namely, when the largest battery is being charged in the shortest available time. When a smaller battery is used with the same size of meter or when a longer time is available for charging, the current will be reduced earlier and therefore a longer time will be required to complete the charge than would be necessary if the location of the contact could be adjusted to suit those lower charging rates.

176. Auxiliary resistance equal to normal resistance. Designating the fixed resistance to reduce the final rate of charge to the finishing rate as the "normal" fixed resistance and the time required to complete the charge through this resistance alone as the "normal" charging time, then if the

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second or auxiliary resistance is equal to the normal, the charging rate during the first stage of the charge will be approximately doubled. The second resistance should have the same carrying capacity as the first. The charge will then be completed at the finishing rate through the normal resistance and the total time required will be from 64 to 73 per cent. of normal.

177. Auxiliary resistance equal to one-half of the normal resistance. If the second resistance is one-half normal, the charging rate during the first stage will be three times normal, and the second resistance should have a carrying capacity double that of the first. The total time required will be from 50 to 63 per cent. of normal.

178. Further reduction in the second charging resistance, to less than half of the normal resistance, cannot be made without encountering excessive charging rates during the initial period of the charge.

179. Main and control conductors. This arrangement requires two control conductors from the ampere-hour meter contacts to the charging panel, in addition to the main conductors, and the charging plug and receptacle must have two auxiliary contacts in addition to the two main contacts. If the circuit breakers and a part of the charging resistance can be mounted on the vehicle, only the two main conductors and a two-point charging plug and receptacle will be required.

180. Single battery charged from motor-generator or other converting apparatus with drooping characteristic. If a single battery is to be charged from a motor-generator set or other transforming apparatus, results the same as those obtained from the modified constant-potential method may be secured, without the use of the fixed resistance, by designing the generator or converter apparatus with the proper drooping characteristic. To accomplish this the value of the fixed resistance and the bus voltage for the modified constant-potential method must first be determined and then the charging apparatus must be designed for a no-load voltage equivalent to the constant bus voltage, and the drop in voltage at full load should be the same as the drop in the fixed resistance with the same current flowing. Characteristic curves of such a type of generator are given in Fig. 18.

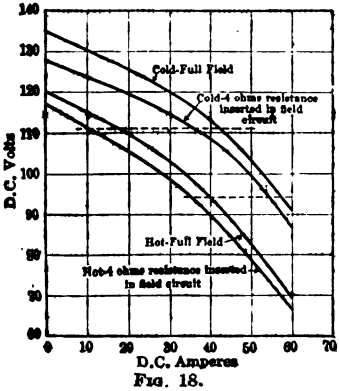


FIG. 18.

181. Charging batteries in series. In cases where there are several batteries to be charged from a high-voltage direct-current bus, it is sometimes the practice to connect the batteries in series across the bus through a suitable fixed resistance. This method will prove satisfactory if all the batteries are discharged to approximately the same state.

182. Precautions in charging batteries in series. In the case of lead batteries, if they are likely to be unequally discharged, the charging rate should be limited to the finishing rate throughout the charge and means should be provided for cutting out any battery that becomes fully charged in advance of the others, connecting in its place a fixed resistance which will produce a voltage drop equivalent to the voltage consumed by the battery cut out.

183. Special types of motor-generator sets for converting alternating-current energy to direct current of suitable voltage are available in various forms and combinations.

184. Individual taper-charging motor-generator sets are in general divided into two classes, low-voltage sets for charging the batteries of industrial trucks and tractors and high-voltage sets, for charging the batteries of trucks and passenger cars. Each set is designed for charging one battery only.

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185. Taper-charging generators are specially wound to provide a tapering charge automatically. For a lead battery, and also in the case of an Edison battery, the tapered charging rate is adjusted so that the average current value is equivalent to the normal constant-current rate for the particular battery.

186. Constant-current charging motor-generator sets. Motor-generator sets are also available having their generators differentially wound in order to maintain automatically an approximate current rate suitable for charging Edison batteries. These sets are capable of automatically charging either one or two Edison batteries having the same electrical characteristics without the services of an attendant to adjust the field rheostat or the battery-charging rheostat to obtain the proper charging rate. As the charge progresses and the battery-e.m.f. rises, the generator-e.m.f. also rises due to the differential action of the fields, automatically maintaining a current rate which is approximately constant.

187. Multiple-battery charging motor-generator sets are designed for charging two or more vehicle batteries in multiple. They are furnished in various voltages and capacities for any of the standard sizes of vehicle batteries. A complete range of sizes for charging batteries of the Edison and the lead types is available, having either shunt-wound or compound-wound generators. From 2.5 to 30 kw. capacity the generators are obtainable in three different ranges of voltage rating, namely 55 to 35 volts, 80 to 51 volts and 100 to 76 volts. The generators can also be obtained in the standard 125-volt classification.

188. Control panels for individual taper-charging motor-generator sets are obtainable for either manual or automatic control, arranged for wall mounting. The panel, which is of slate, is equipped in the non-automatic type with a triple-pole fused knife-switch with special starting clip fuses in generator and motor circuits, starting resistance, generator field rheostat and necessary ammeter and voltmeter.

189. The automatic type of panel is used in connection with a contact-making ampere-hour meter. This panel is equipped with a triple-pole circuit-breaker with shunt-trip attachment, which will automatically open both motor and generator circuits when the battery has been charged to the amount predetermined by the setting of the ampere-hour meter (see Par. 169). This panel is also equipped with ammeter, voltmeter, fuses, generator field-rheostat and special spring-opening switch for starting the set from the battery.

190. Control panels for multiple-charging motor-generator sets are available in various forms and combinations, but the different types are too numerous to permit of detailed description. The general features are covered in the following paragraphs.

191. Sectional type of panel. The panels of sectional type can be assembled in a large variety of possible combinations, thus making it possible to design a very flexible installation. The number of charging circuits may be increased at any time after the switchboard has been installed by the addition of suitable sections and rheostats. However, the combined capacity of the charging circuits in use at one time must not exceed the capacity of the main section. Each panel is comprised of a generator section, an instrument section, and one or more charging sections, together with the necessary charging rheostats. The equipment provides for protection against reverse current and reverse polarity; when an ampere-hour meter is used it also provides for disconnecting the battery from the generator upon completion of the charge. A switchboard of this type centralises the control of a large number of batteries and is convenient to operate.

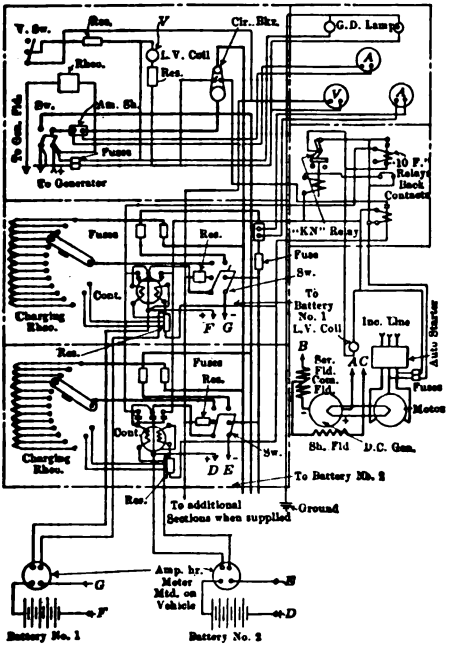
192. Mounting of battery-charging rheostats. In general the battery-charging rheostat is comprised of a resistor of cast-iron grids supported on the rear of each panel section between steel end-frames, with contact buttons and moving arms on the front of the panel section. Bolts through the panel hold the end frames of each charging rheostat to the panel, so that the rheostat forms an integral part of the section equipment.

193. Panel framework and assembly. The sections of each panel are assembled one above another and securely bolted to a vertical angle frame

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other type of frame, of suitable height. It is not advisable to use panels ceeding 84 in. in height because some of the switching apparatus would inconveniently high for the operator. When more sections are required an can be mounted on a frame 84 in. high, they may be arranged in two more panels of uniform height. Where the necessary number of sections not sufficient to make all panels of the same height, blank sections may added to secure uniformity.

194. Typical panel connections. A typical diagram of connections of sectional panel for the control of a motor-generator set is shown in Fig. 19.



IG. 19.—Diagram of connections of a sectional type charging panel for control of a motor generator set.

195. Panel connections for automatic charging. A sectional type panel is also available, with suitable relay equipment, for automatically rminating the charge and shutting down the motor which drives the bat-ry-charging set. The sero contacts of the ampere-hour meters, of which ere is one in each charging circuit, short-circuit the holding-in coils of the attery line contactors. This action causes the battery line contactor to rop out and opens the corresponding circuit. Each battery is disconnected ccessfully, in similar manner, as its charge is completed. The tripping of e last charging contactor opens a relay circuit connected to the low-voltage il of the auto starter, which causes the starter to disconnect the motor-nerator set from the line. A typical diagram of connections of this type panel is given in Fig. 20.

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196. Panel connections for automatically charging a single battery. For the control of a generator where only one battery is to be charged at a time, and where automatic termination of the charge is desired, together

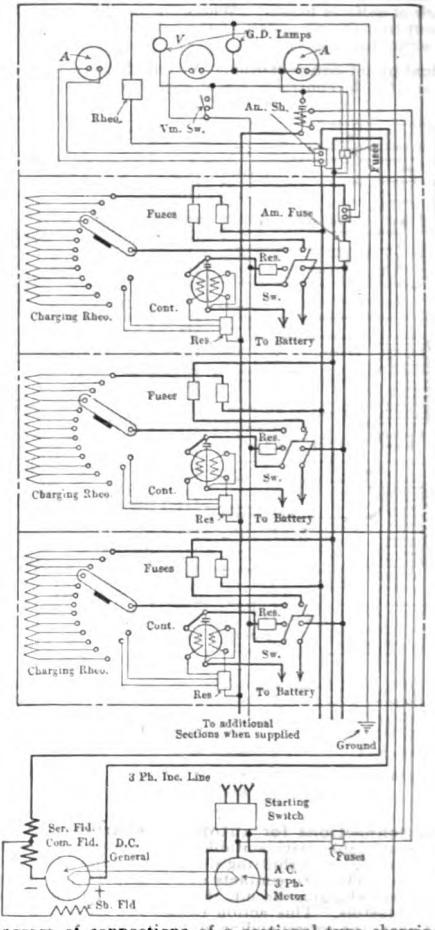


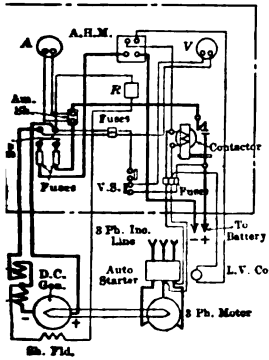
FIG. 20.—Diagram of connections of a sectional type charging panel for control of a motor generating set for full automatic charging.

with low-voltage and reverse-current protection and automatic shut-down of motor-generator set on completion of charge, the typical panel connections are shown in Figs. 21 and 22.

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7. Panels for direct-current supply, of suitable voltage, are similar e sectional types previously described for the control of multiple-charg-notor-generator sets, the principal difference being the substitution of e and meter section for the generator section. A typical diagram of ections is shown in Fig. 23.

8. Panels for automatic charging from direct-current supply. re only one battery is to be charged at a time and where full automatic



o. 21.—Charging an Edison ery from a constant current or tant potential generator.

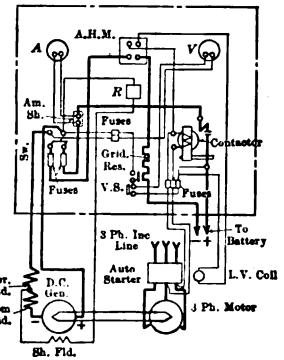


FIG. 22.—Charging a lead battery from a constant potential generator.

Table of Data on Battery-charging Rheostats for Circuits up to 115 Volts Maximum
(General Electric Company)

Charging amperes		Type of cell	No. of cells	No. of steps	Total ohms
Start	Finish				
15	5	Lead	12–18	15	17
20	6	Lead	12–18	15	17
20	5	Lead	20–28	15	13
25	8	Lead	20–28	15	9
30	10	Lead	30–36	15	4
40	10	Lead	30–36	15	4
30	10	Lead	37–40	15	2.6
40	10	Lead	37–40	15	2.6
30	10	Lead	41–44	15	1.5
40	10	Lead	41–44	15	1.5
50	12	Lead	41–44	15	1.28
60	15	Lead	41–44	14	1.0
30	30	Edison A–4	20–40	15	2.8
30	30	Edison A–4	44–60	15	1.7
45	45	Edison A–6	20–40	15	2.0
45	45	Edison A–6	44–60	15	1.2
60	60	Edison A–8	20–32	14	1.4
60	60	Edison A–8	36–44	14	1.0
60	60	Edison A–8	48–60	14	0.72
75	75	Edison A–10	20–32	10	1.17
75	75	Edison A–10	36–44	10	0.81
75	75	Edison A–10	48–60	10	0.60
90	90	Edison A–12	20–32	10	0.96
90	90	Edison A–12	36–44	10	0.68
90	90	Edison A–12	48–60	10	0.48

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charging is desired, the control panel will be similar to that described fo the control of the generator in Par. **196.** Typical connection diagrams ar shown in Figs. 24 and 25.

200. Capacity of battery-charging rheostat. Rheostats for batter charging are specially designed to meet the various conditions fixed by th

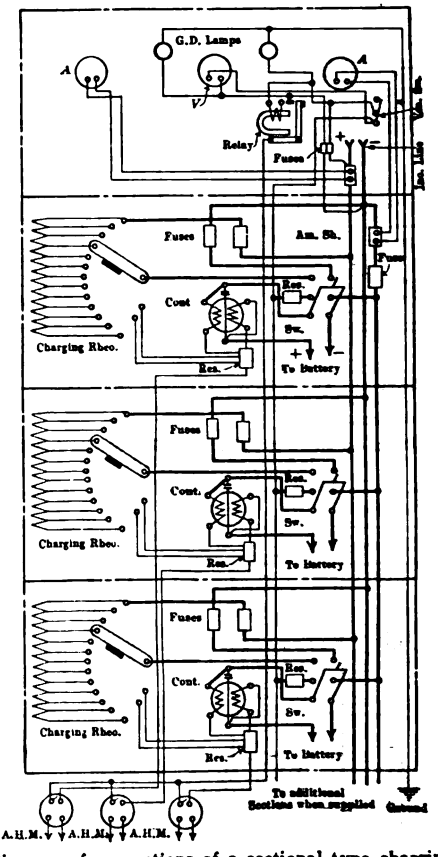


FIG. 23.—Diagram of connections of a sectional type charging panel control of an incoming D. C. line.

number and type of cells in the battery to be charged and the voltage of t direct-current supply circuit. Only by using the proper rheostat for a g battery is it possible to start the charge at the correct rate and reduce current in suitable steps to the final required rate (Paras. **199** and **201**).

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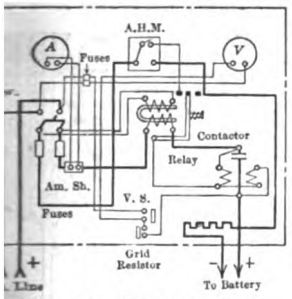


FIG. 24.—Charging a lead battery.

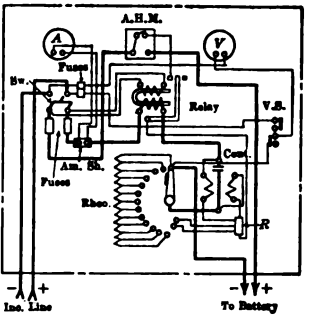


FIG. 25.—Charging an Edison battery.

1. Table of Data on Special Battery-charging Rheostats for Edison Cells, at Normal or Double Normal Rate

	Charging amperes		Type of cell	Number of cells	Number of steps	Total ohms
	Double rate	Normal rate				
Private garage	60	30	Edison A–4	60	14	0.56
	90	45	Edison A–6	60	14	0.34
	120	60	Edison A–8	60	10	0.26
	150	75	Edison A–10	60	14	0.235
	180	90	Edison A–12	60	14	0.23
Public garage	180	30	Ed. A–4–6–8–10–12	60	14	0.565
	120	30	Ed. A–4–6–8	60	10	0.63
	180	90	Ed. A–10–12	60	14	0.23

202. The mercury-arc rectifier and the Tungar rectifier are limited capacity and can therefore be used only where the charging current is thin this limit. Mercury-arc rectifiers can be obtained in capacities up 50 amp., for any desired voltage. This type of rectifier has the disadntage that the charging current must be maintained above a certain minim value and it is not ordinarily self starting. The mercury-arc rectifier s a more or less drooping characteristic, that is, the terminal voltage drops th increased output.

203. Mercury-arc rectifier installation. The general appearance of e rectifier equipment including the reactance, rectifier tube, panel, switches, d instruments is shown in Fig. 26.

204. Non-automatic type of rectifier. One type of rectifier is not tomatic in operation, that is, it will not start or stop itself and if the line ltage fails temporarily, it will not restart. To start this type the bulb ust be tilted by hand by means of a tilting handle.

205. Automatic rectifier. Another type has the same features as the n-automatic and in addition a tilting magnet for automatic starting and relay circuit-breaker. In case of line-voltage failure, which will stop the ctifier, the cutout closes the tilting transformer circuit so that the rectifier ready to restart itself when the power supply is restored. In case of cessive direct current, the cutout coil opens the circuit-breaker contacts.

206. Rectifier applications. For charging a single battery the characristics of a rectifier are not objectionable. The rectifier is applicable where e current value does not exceed the rated capacity. The commercial

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ratings of mercury-arc rectifiers for vehicle-battery charging are shown in table in Par. 206.

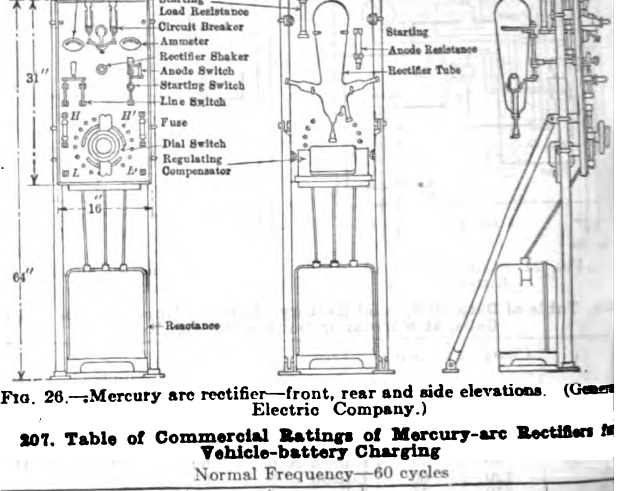


FIG. 26.—Mercury arc rectifier—front, rear and side elevations. (General Electric Company.)

207. Table of Commercial Ratings of Mercury-arc Rectifiers for Vehicle-battery Charging

Normal Frequency—60 cycles

Capacity, amp. (d.c.)	Make	Volts, range (d.c.)	Supply voltage (a.c.)	No. of cells		Approx. shipping weight (lb.)
				Lead	Edison	
30	G.E.	10– 75	110	5–30	7–40	590
	G.E.	20– 75	220	10–30	14–40	590
	West.	28– 85	110	14–32	.....	485
	West.	28– 85	220	14–32	.....	485
	G.E.	30– 83	110	12–32	16–44	540
	G.E.	30–118	220	14–46	16–62	540
	G.E.	10–100	110	5–38	7–54	590
	G.E.	20–120	220	10–46	14–65	590
	West.	40–120	110	20–44	.....	575
	West.	40–120	220	20–44	.....	575
	G.E.	75–175	220	32–68	54–95	590
50	G.E.	10– 75	110	5–30	7–40	660
	G.E.	20– 75	220	10–30	14–40	660
	G.E.	10–100	110	5–38	7–54	660
	G.E.	20–120	220	10–46	14–65	660
	G.E.	75–175	220	32–68	54–95	660

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SECTION 18

ELECTRIC SHIP PROPULSION

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SECTION 18

ELECTRIC SHIP PROPULSION

SHIP RESISTANCE

1. General law of ship resistance. The frictional resistance of any well-designed ship is roughly proportional to the square of the speed. Consequently at half speed the frictional resistance will be only one-quarter of the frictional resistance at full speed. Since the power required to propel a ship is proportional to the product of the frictional resistance and the speed, it follows that the power delivered from the propeller is proportional to the cube of the speed. Thus at half speed the output from the propeller is only one-eighth of the output at full speed. This relation is not exact but is nevertheless widely employed for approximate calculations. For large, high-speed vessels, such, for instance, as the "Mauretania," the power required for driving the ship increases, at high speeds, even more rapidly than as the cube of the speed, as the result of decreasing propeller efficiency. For ships operated at widely varying speeds, it has thus been a consideration of much importance that the economy of the engine should be fairly high over a wide range not only of loads but of speeds.

2. Fundamental data on ship resistance. By analysis of the published data of a large number of modern ships of a wide variety of speeds, displacements and types, the results in the following table have been obtained for the frictional resistance reduced to the common reference base of a speed of 20 knots (1 knot is a speed of 1 nautical mile per hour. One nautical mile = 6,080 ft. = 1,850 meters).

3. Table of Approximate Values for the Frictional Resistance of Ships

Displacement in (2,240-lb.) tons	Frictional resistance in lb. per ton, at a reference speed of 20 knots
500	42
1,000	34
2,000	26
4,000	18
8,000	12
16,000	9
32,000	7

It will be seen from the values in the above table that, for a given speed, the frictional resistance per ton gradually decreases with increasing size of ship and attains a very low value in large ships.

4. Estimation of the thrust horse-power required. The power delivered from the propeller, is termed the thrust horse-power. Consider the case of a 4,000-ton ship when proceeding at a speed of 22 knots. From the table in Par. **3**, the frictional resistance at a speed of 20 knots is given as 18 lb. per ton. For a speed of 22 knots, the frictional resistance of the ship will be:

$$4{,}000 \times \left(\frac{22}{20}\right)^2 \times 18 = 87{,}400 \text{ lb.}$$

$$\text{Output from propeller} = \frac{87{,}400 \times 22 \times 6{,}080}{60 \times 33{,}000} = 5{,}900 \text{ thrust h.p.}$$

Again, for a 24,000-ton ship proceeding at a speed of 14 knots:

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$$\text{Frictional resistance} = 24{,}000 \times \left(\frac{14}{20}\right)^2 \times 8 = 94{,}000 \text{ lb.}$$

$$\text{Output from propeller} = \frac{94{,}000 \times 14 \times 6{,}080}{60 \times 33{,}000} = 4{,}040 \text{ thrust h.p.}$$

Of course in actual service, these values will vary tremendously with wind, ave, tide, condition of ship's bottom, disposition of cargo, arrangement superstructure and other varying conditions. Furthermore the values ven correspond with normal designs of average vessels. It is to be obrved, however, that reasonable extremes in type of vessel do not occasion eat departures from representative values of the frictional resistance.

5. Ship momentum. When increasing the speed of a ship, power must expended in order to provide the greater momentum associated with the gher speed. This power is in addition to that required to overcome friction. Consider the acceleration of a 24,000-ton[6] ship from rest up to a speed 14 knots. The formula for E, the energy of momentum, is:

$$E = \frac{1}{2}\frac{W}{g}V^2 \qquad (1)$$

here: W = weight in pounds,
g = acceleration of gravity in feet per second per second (= 32.2),
and V = speed in feet per second.

In our example we have:

$$W = 24{,}000 \times 2{,}240 = 53{,}860{,}000 \text{ lb.}$$

$$V = \frac{14 \times 6080}{3600} = 23.6 \text{ ft. per second.}$$

$$E = \frac{53800000 \times 23.6^2}{2 \times 32.2}$$

$$= 467{,}000{,}000 \text{ ft-lb.}$$

[1 h.p. = 33,000 ft-lb. per minute.
∴1 h.p-hr. = 33,000 × 60 = 1,980,000 ft-lb.]

$$\therefore E = \frac{467}{1.98} = 236 \text{ h.p-hr.}$$

6. Acceleration. If the acceleration is accomplished in 3 min. and at e uniform rate of $\left(\frac{23.6}{3 \times 60} =\right)$ 0.131 ft. per second per second, then the itput from the propeller for providing this acceleration is:

$$(60/3) \times 236 = 4{,}720 \text{ thrust h.p.}$$

We have already seen (Par. 4) that, at a speed of 14 knots, an output of 040 thrust h.p. is required for overcoming the frictional resistance. Consequently when accelerating the ship from rest up to a speed of 14 knots, in min. the output from the propeller gradually increases from 4,720 thrust p., at the moment the ship starts, up to 4,720 + 4,040 = 8,760 thrust h.p., the completion of the acceleration, and then decreases to 4,040 thrust h.p., nen constant speed is attained.

In practice, the acceleration is not at a uniform rate but gradually creases as the ship gathers speed.

7. Retardation. It is interesting to consider the conditions attending emergency reversal when the ship (Par. 6) is proceeding at a speed of knots. In order to bring the ship to rest in 3 min. (neglecting the losses the machinery and the resistance of the ship), the propellers must, ter reversal, *impart to the water* 236 h.p-hr. of energy. It may be assumed that 30 sec. is occupied in bringing the propellers up to speed in the verse direction and that, during this time, the ship travels: (30/3,600) 14 × 6,080 = 710 ft.

For the remaining 2.5 min. (150 sec.) the propellers must impart to the ter nearly 236 h.p-hr. (say 200 h.p-hr.) of energy. The average output m the propellers is: (60/2.5) × 200 = 4,800 thrust h.p. If the retardation uniform, the average speed during these 150 sec. is: 23.6/2 = 11.8 ft. r second and the distance traversed is: 150 × 11.8 = 1,770 ft., the total dis-

[6] Throughout this section the 2,240-lb. ton will be employed.

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tance traversed during the 3 min. occupied by the manœuvre is: 710+1,770 = 2,480 ft.

Since the momentum increases as the square of the speed, and since, as will be seen in Par. 17, the efficiency of propellers is only of the order of 60 per cent., the bringing to rest of a 24,000-ton ship in 3 min. from a speed of 25 knots, would require an average output from the engines to the shaft, of the order of: $\left(\frac{25}{14}\right)^2 \times \frac{100}{60} \times 4{,}800 = 25{,}500$ h.p.

During such a manœuvre, the ship would cover a distance of over 4,000 ft.

Reciprocating engines are very effective for astern manœuvres, but since steam turbines are non-reversible and since it is economically impracticable to provide astern turbines with any such capacity as that of the ahead turbines, ships equipped with steam turbines, driving the propellers directly or through mechanical gearing, are deficient in capacity for prompt astern manœuvres. The seriousness of any such deficiency is too apparent to require comment. See Par. 9.

8. Emergency power requirements. In the ordinary course of navigating a ship, the power required is, from time to time, far in excess of that required in a smooth sea to maintain constant speed. In a heavy sea the ship's speed is repeatedly and abruptly decreased by impact with waves. Under such circumstances the progress of the ship is accompanied by a succession of cycles which impart to it the momentum which is absorbed by impact with the waves. Under these circumstances, not only must the output of the engines be great enough to overcome the increased frictional resistance, but also to provide, again and again, the energy of momentum corresponding to the speed of the ship. The power equipment of a ship should be estimated with due regard to whether it will navigate inland waterways or whether it is destined for ocean transportation. An instance of the extreme fluctuations of load occurring in bad weather at sea in the case of the Wulsty Castle is given in Par. 74.

9. Backing tests (retardation); engines versus turbines. In a paper by Capt. C. W. Dyson, U.S.N., entitled "Engineering Progress in the United States Navy" read before the Society of Naval Architects and Marine Engineers at New York on Nov. 21 and 22, 1912 (see page 198, *The Engineer*, for Feb. 14, 1913), the author states that in backing tests of the battleship "Delaware," which is equipped with two sets of triple-expansion engines, 1 min. and 52 sec. were required to bring the vessel dead in the water from a speed (ahead) of 21 knots; and that in similar tests on the battleship "Utah," which is equipped with Parsons turbines, 4 min. and 44 sec. were required to bring the vessel dead in the water from a speed (ahead) of 20 knots.

On page 492 of *Engeneering* for April 10, 1908, in a description of tests of the turbine ship "Lusitania," it is stated that with the vessel proceeding at a speed of 22.8 knots, 3 min. and 55 sec. were required from the instant of signalling "full-speed astern" to bring the ship to rest. In this time, the ship run a distance of three-quarters of a mile. These figures indicate the great inferiority of the turbine ships "Utah" and "Lusitania" with respect to prompt stopping, as compared with the "Delaware," equipped with reciprocating engines.

10. Formulas for determining the power required for propulsion. Naval architects and marine engineers employ to good purpose, in calculating the power required for ship propulsion, a large collection of coefficients and ratios which represent the results of accumulated experience. In the limited space it would be inexpedient to deal categorically with all of these coefficients and ratios.

11. Block coefficient. In the design of cargo boats a leading consideration relates to having a high "block coefficient," *i.e.*, a high ratio of displacement (D), to the weight of a block-shaped volume of water whose length, breadth and depth are equal to the ship's length (L), beam (B), and draft (H), respectively. The "block coefficient" of fast ocean liners and of warships, with the lines essential to speed, is only of the order of 0.6 to 0.7; for cargo boats the carrying capacity is of such importance that designers use block coefficients of 0.8 and higher are employed, and with only moderate increase in frictional resistance per ton of displacement. Even in high-speed cargo boats the length must be maintained in fairly high propor-

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to the tonnage capacity, partly in order to maintain the frictional resistance at a reasonably low value, and largely in order that the ship may be passed through locks, and in general conform to the requirements of such service. The "**beam draught**" ratio (B/H), and the "**displacement length**" ratio $D \div (L/100)^3$, are also amongst the criteria employed in this connection.

18. The admiralty formula. Naval designers and marine engineers (especially in Great Britain), have made considerable use of the "admiralty formula," and although it dates from the period before the advent of the marine steam turbine, it is still widely used. The "admiralty formula" expresses the indicated horse-power (i.h.p), in terms of the two-thirds power of the displacement, the cube of the speed, and a factor, C, known as the "**admiralty displacement coefficient.**" The formula is:

$$\text{indicated horse-power} = \frac{D^{\frac{2}{3}} \times V^3}{C} \qquad (3)$$

It will be seen that the length (L) of the ship does not enter directly into this formula but is embodied in C, the "admiralty displacement coefficient."

Other formulæ and data relating to ship resistance, and to the power required for propulsion, are given in Taylor's "Speed and Power of Ships;" John Wiley & Sons, New York, 1910, and in Chapters II and IV of Hobart's "Electric Propulsion of Ships;" D. Van Nostrand Co., New York, 1911.

PROPELLER CHARACTERISTICS

19. General. The screw propeller was first employed for ship propulsion thousands of years ago by the Chinese. The steam-driven screw propeller came into wide use during the last half of the nineteenth century. The first quarter of the twentieth century is witnessing the extensive adoption of electrical transmission from the steam engine or oil engine to the propeller. This introduces various advantages which will be set forth in later paragraphs. At present it is desired to dwell on the very important advantage that the method permits greater freedom in the choice of propeller speed.

14. Propeller thrust, diameter and speed. It will be impossible to touch upon more than the mere elements of the characteristics of propellers. In Par. 4, we briefly discussed a 24,000-ton ship for operation at a speed of 14 knots. At this speed the output required from the propeller for overcoming frictional resistance was estimated to be 4,049 thrust h.p.; now assume that 5,000 thrust h.p. will be provided. At a speed of 14 knots the corresponding thrust will be:

$$\frac{5{,}000 \times 33{,}000 \times 60}{14 \times 6{,}080} = 116{,}000 \text{ lb.}$$

It is usual in large ships to design the propellers for a **pressure** of not over **12 lb. per square inch of projected surface.** The projected surface of a propeller is the component of the area of the blades corresponding to a surface normal to the axis of the shaft. Therefore the projected surface should be $116{,}000/12 = 9{,}700$ sq. in.

The surface ratio is the ratio of the projected surface to the area of a circle whose diameter is equal to that of the tips of the propellers blades. We may assume that we shall employ a design having a surface ratio of 0.35. Consequently in the present instance we must provide a gross area of $9{,}700/(0.35 \times 144) = 192$ sq. ft. If we employ a **single propeller**, its diameter should be: $\sqrt{(4 \times 192)/\pi} = 15.6$ ft. For a peripheral speed of 6,000 ft. per minute we arrive at a rotational speed of $6{,}000/(15.6 \times \pi) = 122$ r.p.m.

For the alternative of employing **two propellers**, and again assuming a surface ratio of 0.35, a pressure of 12 lb.per square inch of projected area, and a peripheral speed of 6,000 ft. per minute, we arrive at a diameter of $(0.707 \times 15.6 =)11.0$ ft. and a speed of $(1.414 \times 122 =)173$ r.p.m.

Many other considerations enter into the determination of the preferable design. The number of blades, and their shape, size and pitch, have a far-reaching influence on the result, as have also the peripheral speed and the pressure per square inch of projected area. The determination of the most favorable disposition of the propellers with reference to the hull and to one another, is another matter of much importance. The range of practicable diameters is also affected by the size of the ship and by its lines. If the propellers are to be well immersed in all weathers the permissible diameter is quite limited in ships with shallow draught.

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15. Propeller slip. No reference has yet been made to the important consideration of the slip. The slip of the propeller is expressed as the percentage by which the speed of the ship is less than the speed corresponding to the pitch of the propeller. Let us illustrate this by the example of the 15.6-ft. propeller, which, when driven at a speed of 122 r.p.m. (Par. 14) should propel the ship at a speed of 14 knots, or $(14 \times 6,080)/60 = 1,420$ ft. per minute. At each revolution, the ship must travel a distance of $1,420/122 = 11.6$ ft.

Were there no slip, the propeller would be designed with a pitch of 11.6 ft.; in other words, the "**pitch-ratio**" (the ratio of the pitch to the diameter), would be $11.6/15.6 = 0.75$. The relations between the ship and the other characteristics of a propeller are highly complex and a knowledge of them is one of the assets of the naval designer. Such knowledge at present is in process of evolution, and forecasts of the performance of propellers, as well known, are likely to be very wide of the mark. Notwithstanding the elaborate and expensive tests on models, which often precede the construction of an important ship, great modifications in the propeller equipment are often made during her first few years of service. Assuming (for explanatory purposes) that experience has indicated that the slip will be 15 per cent. in the present case, it is seen that instead of a pitch of 11.6 ft. (corresponding to a pitch-ratio of 0.75), the propeller must be designed with a pitch of $\frac{11.6}{0.85} = 13.6$ ft., corresponding to a pitch-ratio of $(13.6/15.6 =) 0.87$.

16. Compromise design. It is hardly necessary to dwell further upon the large number of factors entering into the design of propellers. The object in view is to arrive at an economic balance between good efficiency, satisfactory capacity in executing all manœuvres required of the ship and conformity with the requirements of the machinery from which it is driven. It was possible to arrive at a more satisfactory compromise among all these requirements when reciprocating engines were customarily employed, than has been the case since the advent of the steam turbine. This is for the reason that the **efficiency** of low-speed propellers is decidedly higher than that of high-speed propellers. In the case of ships of any considerable size, it would be utterly out of the question to design good propellers for speeds remotely approaching the high speeds of *efficient* steam turbines.

17. Best speed of propellers. It does not follow that, even with electric drive, it is desirable to adopt exceedingly low propeller-speeds. On the contrary, when due consideration is given to the efficiencies of (1) propellers, (2) electrical machinery, and (3) prime movers, and to their weights and costs, a compromise speed will usually be arrived at which involves at least a small amount of sacrifice in propeller efficiency. A consideration which frequently justifies the fitting of propellers of smaller diameters and higher speeds than are consistent with maximum efficiency, relates to ensuring as complete immersion as possible under all conditions of wind and weather and load, in order to minimise "racing."

Surprise may be occasioned by the statement that it is rare to realise **propeller efficiencies** of over 60 per cent., and that for representative modern ships of large size, the propeller efficiency is usually of the order of only 50 per cent. for turbine-driven ships, as against some 55 per cent. for ships equipped with reciprocating engines. Considering the greater flexibility resulting from the electric drive, and the gradually increasing knowledge of propeller design, it would appear that 60 per cent. should be kept in mind as a reasonable propeller efficiency for ships equipped with electric gearing, and that an improvement up to some 65 per cent. should be realized in favorable cases in the not-distant future. Allusions to propeller efficiencies of the order of 70 per cent. to 75 per cent., which are found in treatises dealing with the design of propellers, must be relegated to the category of theoretical abstractions which can be approached in tests of models, but which require the ruthless application of large allowances in order to arrive at values which can be realized in actual practice.

In a paper entitled "A Case for Electric Propulsion" read in June, 1914, before the Institution of Naval Architects, the authors, Mr. Henry A. Mavor and Mr. John Reid, stated:

"There are not 10 per cent. of the merchant vessels now afloat which would not be most efficiently propelled by screws designed to turn at revolutions not exceeding 80 per minute."

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18. Limits of propeller size and power. It is well to call attention to he enormous power which can be delivered by a single propeller. In driving he "Mauretania" at 26 knots, an average speed at which she has made omplete journeys across the Atlantic, the total thrust horse-power amounts o fully 36,000 h.p., or if equally distributed among the four propellers, ,000 h.p. per propeller. This corresponds, with her present equipment of our-bladed screws, to an output of 2,250 h.p. per blade. The propeller di- ameter is 15 ft., corresponding to a gross area of 176 sq. ft. The output may hus be reduced to: 9,000/176 = 51 thrust h.p. per square foot of gross area. Taking the projected area, in the case of the Mauretania's latest propellers, s probably being some 40 per cent. of the gross area at the pitch circle, we ave also: 51/0.40 = 127 thrust h.p. per square foot of projected area. No ignificance is to be attached to these large values, as they result from the mployment of propellers of a speed distinctly too high to be compatible vith good efficiency, and which have, furthermore, too small an area for ffective manœuvring.

The turbines of the British battle cruiser "Tiger" were designed to deliver 100,000 shaft h.p. at the vessel's maximum speed of 31 knots. Her four high-speed propellers probably did not have an efficiency of over 50 per cent., giving a thrust horse-power of some 50,000 h.p. or 12,500 h.p. per propeller.

19. Multiple propellers. In the early stages of the development of the marine steam turbine, engineers failed to realize that its natural speed was far in excess of speeds consistent with good propeller characteristics. Consequently vessels were equipped with propellers of such small diameters as to embody merely the necessary mechanical strength at high speeds, and the necessary area was obtained by resorting to the use of several (multiple) small propellers. In certain instances this was carried to the extreme of installing more than one propeller on a single shaft.

In 1894 on the occasion of the first trial of the historical "Turbinia" (of 45 tons displacement), she was fitted with only one shaft and a single two-bladed propeller of 30 in. diameter and 27 in. pitch. As thus fitted, the "Turbinia" was quite inoperative owing to intense cavitation. The slip was 49 per cent. She was then re-fitted with three propellers on the same or single shaft; these propellers were spaced from each other by three diameters and yielded a vessel speed of 20 knots, the propeller slip being 38 per cent. In 1896 the "Turbinia" was again re-fitted, three turbines being installed. Each of the three shafts carried three 18-in. diameter screws with a pitch of 24 in. She attained a speed of 34 knots with a turbine speed of 2,200 r.p.m. and slips of 17 per cent. on the middle shaft and 25 per cent. on the side shafts. In 1903, the "Turbinia," after having her *nine* 18-in. propellers replaced by *three* propellers of 28 in. diameter with a 28-in. pitch (there being one propeller on each shaft), was again tested, and showed about the same economy up to a speed of 17 knots, and a quite considerable increase in speed for a given steam consumption, for all speeds between 18 knots and 28 knots. Further particulars of the "Turbinia" tests may be found in a paper by Parsons, read before the Institution of Naval Architects on June 26, 1903.*

SYSTEMS OF PROPELLER DRIVE

20. Reciprocating steam engines. There are three leading advantages possessed by the reciprocating engine for marine propulsion. These are:

(a) The natural speed of the marine type of reciprocating steam engine is of the same order as the natural (most efficient) speed of the screw propeller.

(b) The reciprocating steam engine may be designed for good economy over a wide range of speeds and loads, and for best economy at some intermediate speed and load.

(c) The reciprocating steam engine may readily be reversed and may exert great power during astern running. It is susceptible of ready control at all speeds including "dead-slow" speeds, and consequently endows the ship with excellent manœuvring ability.

The case for the reciprocating engine for marine propulsion, with special reference to the requirements of the United States Navy, was very ably presented by Capt. C. W. Dyson, U. S. N., in a paper entitled "Engineering

*Stevens and Hobart. "Steam Turbine Engineering," Chap. XXIII, Whittaker & Co., London, 1906.

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Progress in the U. S. Navy" read before the Society of Naval Architects and Marine Engineers in November, 1912* (Par. 21).

The **disadvantages** of reciprocating steam engines relate chiefly to their great weight and bulk as compared with modern high-speed steam turbines. This disadvantage is serious where space and weight have as great significance as in a ship. But as pointed out in Par. 21, Capt. Dyson did not find any disadvantage in this respect in certain typical warships, when reciprocating engines were compared with *low-speed* marine steam turbines for direct connection to the propeller shafts. The initial cost of the reciprocating engine is relatively great when compared with the modern *high-speed* steam turbine. It is more impracticable to profit to so great an extent, as with the steam turbine, from the decreased steam consumption attending the high vacuums which are readily and economically attainable at sea. The reciprocating engine consumes far more lubricating oil than does the steam turbine, and also the wages item associated with the engine-room personnel is greater.

21. Capt. Dyson on relative advantages of steam engines and low-speed turbines in the U. S. Navy. The following quotations are made from Capt. Dyson's paper:† "This excessive falling-off in efficiency of propulsion under adverse conditions of wind, sea, and of ship's bottom, are characteristics of turbine-driven vessels." . . . . . "Should the duties of a vessel be such that she be required to steam for long periods and long distances at speeds much lower than her designed maximum speed, a less fuel expenditure per day will be required, and consequently a greater cruising radius will be obtained and less frequent re-coaling necessitated should reciprocating engines be fitted rather than turbines for propelling purposes. Should, however, the vessel operate from a fixed base, only doing sufficient cruising to ensure that the machinery is kept in efficient condition in readiness for forced runs to any threatened point, the value of fuel economy at low speeds becomes minimised, and, where the maximum speed of the vessel does not exceed 21 to 22 knots, either turbines or reciprocating engines may be used, the choice being dependent upon other factors than economies, which are practically equal at these speeds." . . . . . "The claim is frequently made by the turbine advocates that while the reciprocating engine, when new, is undoubtedly more economical than the turbine at small fractions of designed power, this advantage is soon lost in actual service, due to excessive wear of piston and valve rings causing large losses through heavy leakage of steam. The turbines, not being subject to such frictional wear, would, on the other hand, retain their original economy indefinitely. Practical experience with both types of engine in actual service comes very far from justifying this conclusion." . . . . . "In the cases of the main engines of the three scouts, 'Birmingham,' 'Salem' and 'Chester,' the 'Birmingham,' with reciprocating engines, has always been ready for service, while her sisters have been repeatedly laid up at the yards for overhaul of the turbines." . . . . . "For existing conditions nothing can be saved in boiler-room weights or space by adopting turbines, as the same boiler power is required in the two cases. In the engine rooms, for these powers, however, the reciprocating engine has a decided advantage in both weight and space required. Thus, in the 'Delaware,' 'North Dakota' and 'Utah,' the engine-room weights and space required are as follows:

	Delaware (reciprocating engines)	North Dakota (Curtis turbines)	Utah (Parsons turbines)
Engine-room weights, dry tons‡	728.0	731.0	865
Engine-room weights, wet tons.	773.0	786.0	920
Engine-room, length, ft.....	44.0	44.0	48.
Engine-room, total width, ft...	50.5	50.5	52.
Engine-room, sq. ft., floor space.	2,222.0	2,222.0	2,496.

* *The Engineer*, London, Feb. 14, 1913, p. 184; Feb. 21, 1913, p. 208.

† Dyson, Capt. C. W. "Engineering Progress in the U. S. Navy;" Society of Naval Architects and Marine Engineers, Nov., 1912.

‡ "Wet and dry tons" relate to the engine-room weights with and without water in the boilers.

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While the reciprocating engine has a decided advantage in the features of weight and space required, under present conditions these advantages would disappear should the necessary power to be developed be increased considerably above what is now asked for, and the advantage would rest with the turbine." . . . . . "Basing the choice between reciprocating engines and turbines for battleship propulsion under existing conditions of speed and power upon the above comparison of relative advantages of the two types, the advantage appears to rest most decidedly with the reciprocating engines." It must be emphasized that this was written in 1912 when steam turbines were direct connected to the propellers and that with geared turbines the conclusions require modification.

22. Relative economy of steam engines. In the case of large, compound, triple-expansion and quadruple-expansion marine engines the economy falls but little behind that obtained in modern, high-speed turbines for the same power, and is much better than that of steam turbines designed to operate at *speeds so low* as to permit direct connection to the propellers.

23. Examples of steam-engine economy. In a paper by C. Waldie Cairns* the result of 1.70 lb. of coal per indicated horse-power-hour with triple-expansion engines was given for a 36-hour trial of the 10-knot "Cairngowan" on Feb. 6, 1913. The corresponding water consumption was 15.2 lb. per indicated horse-power-hour; steam pressure, 175 lb. per square inch; vacuum, 26.8 in.; propeller speed, 61.7 r.p.m.; displacement, 9,950 tons, draft, 23 ft. 10 in.; length, 371 ft.; beam, 51 ft. See Par. 34 and 35.

Elsewhere it has been stated on excellent authority that there are many ships which, even without superheaters, are working at 1.3 lb. and 1.4 lb. per indicated horse-power-hour (triple expansion) for all purposes.† In an editorial on p. 349 of *Shipbuilding and Shipping Record* for March 19, 1914, allusion is made to the estimate that with the combination of a reciprocating unit exhausting into a low-pressure turbine geared to a propeller shaft the water rate for large ships could be cut down to 8.5 lb. per hp.-hr.

24. Internal-combustion engines. The only types of internal-combustion engine as yet developed which can come in for reasonable consideration for marine propulsion are those employing oil as fuel. The impracticability of providing space on board ship for gas producers and auxiliary plant precludes gas engines from consideration, so far as can be foreseen at present. Indeed it is the elimination of any equivalent to the steam-raising plant which is chiefly instrumental in giving the oil engine any standing as a prime-mover for ship propulsion.

Space and weight are factors of supreme importance on board ship, and it is the consideration that four-tenths of a ton of crude petroleum (or probably even of residue), will suffice for supplying the same number of shaft horse-power-hours to the propellers as would be supplied by burning 1 ton of coal‡ under boilers in a steam plant, that is proving so attractive to marine engineers and shipowners, even though the outlay for 0.4 ton (120 gal.)§ of crude petroleum will be much greater than for 1 ton of good coal. The advantage of the space and weight saved is of no small account, and for medium-sized and small-sized ships it should often outweigh the accompanying handicap of the increased outlay for fuel and the very great initial outlay for engines requiring the finest of workmanship in their manufacture and skilled attendance and adjustments during service. It is characteristic of oil engines as at present developed, that the weight of an engine of twice the capacity of a reference engine is, for the same speed, usually

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* Cairns, C. W. "A Comparative Trial between the Triple-expansion Engine and Geared Turbine in Cargo Steamers." Also see *Shipbuilding and Shipping Record*, Apr. 3, 1913; p. 6.

† *Engineering*, London, July 19, 1912; p. 91.

‡ Crude petroleum is taken as having 19,000 B.t.u. per pound and coal as having 15,000 B.t.u. per pound. $0.4 \times 19{,}000/15{,}000 = 0.51$. Thus the statement in the text is based on obtaining with the oil engine only twice the efficiency from fuel to shaft, as in the steam plant. While better results are guaranteed and obtained, it is desirable at so early a stage in the development of the internal combustion engine to be conservative in estimating its performance.

§ The U. S. gallon, equal to the volume of 8.35 lb. of water or about 7.5 lb. of crude petroleum, is taken here.

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more than twice as great as the weight of the engine of reference. Furthermore the economy is no better in the larger engine.

This state of affairs is in striking contrast with the characteristic of steam engines and steam turbines, that the greater the capacity the less the weight per horse-power and the less the steam consumption per horse-power-hour. On the other hand, *in small sizes* the economy of the steam turbine is not good, and it requires a large outlay for boilers and condensers.

25. Limitations of the oil engine. It appears that for installations of the order of **2,000 h.p. or less,** there should be a large field for the oil engine notwithstanding the greater outlay for fuel. As compared with the steam turbine, the oil engine is handicapped by a considerable further outlay for lubricating oil. But taking into account the small quantity of fuel and the absence of any equivalent to the boiler plant, the advantage will usually be for less than some 2,000 h.p., remain with the oil engine *provided* the installation consists of several small sets, or subdivided units, with individual **electric drive** between engine and propeller. The last feature is necessary to overcome the relative unreliability of the oil engine and to enable repairs to be made without stopping the propellers.

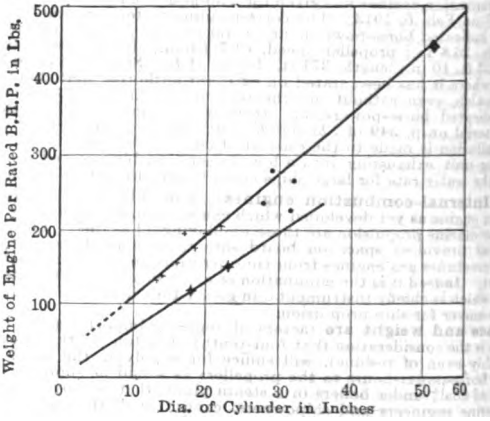


FIG. 1.—Weights of gas-engines of different dimensions.

Except for very small outputs, the oil engine is particularly ill-suited for *direct connection* to the propeller, for the reason that for starting and for reversing, a considerable supply of compressed air must be available. Furthermore, the efficiency of the oil engine decreases rapidly as the load decreases, and also it is satisfactory only at normal speed. Sight must not be lost of the fact that oil engines of the sizes which come into consideration for the purpose are expensive machines and much less rugged and reliable than steam turbines or steam engines. The handicap in first cost and fuel cost must be equated against the greater earning power of the ship consequent upon the space and weight saved and made available for cargo.

26. Weight of internal combustion engines. It is important that sight should not be lost of the relatively great weight of internal-combustion engines. Dr. Diesel stated* (in 1912) that the more recent engines of his

* Diesel, R. "The Diesel Engine and Its Industrial Importance, Particularly for Great Britain;" Proceedings Institution of Mech. Engineers, 1912.

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type (double-acting, two-stroke-cycle) weighed only some 110 lb. per horse-power. Mr. Dugald Clerk in the discussion of Dr. Diesel's paper gave the table of weights in Par. 26 and also the curves which appear in Fig. 1 and Fig. 2.

It is the order of magnitude of these weights, relating to four-stroke-cycle engines, which has occasioned the strong tendency to develop the larger capacities in two-stroke-cycle engines.

A single acting, four-stroke-cycle, low-speed, 800 b.h.p. Diesel engine is considerably heavier than any of the engines shown in Fig. 2, as it has a weight of some 600 lb. per brake horse-power. Retaining the same low speed,

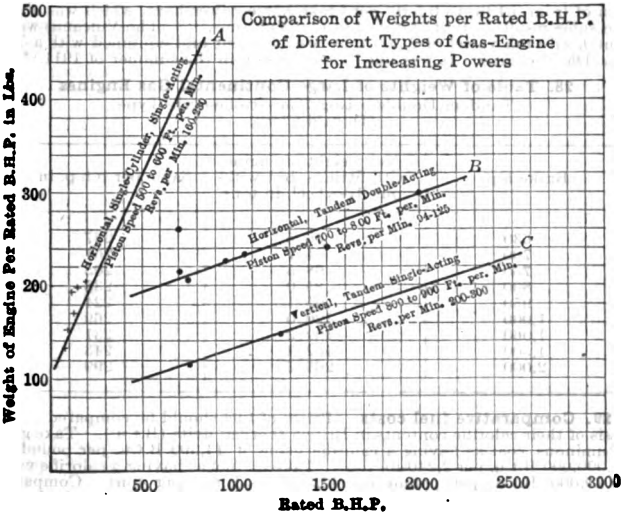


FIG. 2.—Comparison of weights per rated brake h.p. of different types of gas-engine for increasing powers.

but resorting to a double-acting two-stroke-cycle, the weight comes down to 238 lb. per brake horse-power; and in 1912 the weight of high-speed Diesel engines of the double-acting two-stroke-cycle type had, in some instances, been brought down to 116 lb. per brake horse-power. The above data of weights of Diesel engines present a striking contrast to the low weights per brake horse-power which are being obtained in large steam turbines.

27. Diesel marine engines. The "Selandia," "Fionia" and "Jutlandia" are sister ships; each is 370 ft. long and 53 ft. beam. Each ship is fitted with two four-stroke-cycle vertical, single-acting Diesel engines and each of the two engines comprises eight cylinders and has a rated capacity of 1,250 i.h.p., or a total of 2,500 i.h.p. per ship. The speed at sea is 130 r.p.m. In a paper by Mr. I. Knudsen entitled "Results of Trials of the Diesel-engined Sea-going Vessel 'Selandia,' read on March 28, 1912, before the Institution of Naval Architects, the results of the trial trips are given. It is stated that reversal of the engines from full speed ahead to full speed astern can be carried out in 20 sec. The fuel oil is stored in the double bottom of the vessel, and sufficient storage capacity is provided for a continuous journey of about 30,000 miles. After three short trial trips the "Selandia" made a journey across the North Sea from Copenhagen to Aalborg with a cargo consisting of about 2,000 tons of cement. The fuel consumption (including all oil used for auxiliaries, but excluding that used for heating the vessel), was

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0.363 lb. per indicated horse-power-hour developed by the main engines. On the basis of a calorific value of 19,000 B.t.u. per pound of fuel, this works out at (0.363 × 19,000 =) 6,900 B.t.u. per indicated horse-power-hour. The thermal equivalent of 1 h.p-hr. is 2,550 B.t.u. and therefore the thermal efficiency was 2550/6900 = 37.0 per cent.

Since no deduction was made for the fuel consumed by auxiliaries, and since the efficiency figure relates to the efficiency in actual service at sea, the result must be regarded as very good indeed. In the course of the discussion of the paper Mr. J. T. Milton stated that "the brake horse-power would be about 82 per cent. of the indicated horse-power, according to general practice. Assuming this to be correct for the 'Selandia,' it would give a consumption of from 0.4 lb. to 0.5 lb. per brake horse-power-hour, which was about the same result as that obtained in the 'Vulcanus.'" (The Vulcanus was a Dutch oil-tank vessel of 2,500 tons displacement and equipped with a 500-h.p. Diesel engine. It was put in commission in the summer of 1911.)*

28. Table of Weights of Large Continental Gas Engines
Tandem Double-acting Four-stroke-cycle Type
(Dugald Clerk)

Brake h.p	Net weight of engine with fittings, but without fly-wheel, in tons	Same per b.h.p. in lb.
630	66.5	237
700	81.7	261
750	68.5	205
800	85.0	238
950	95.1	224
1,000	120.0	269
1,060	109.3	231
1,500	162.3	243
2,000	266.5	299

29. Comparative fuel costs. Prices of fuel should be compared on the basis of their calorific contents in British thermal units (B.t.u.). Take good bituminous coal as having a calorific value of 14,300 B.t.u. per pound (or 32,000,000 B.t.u. per 2,240-lb. ton). Take oil fuel as having a calorific value of 19,000 B.t.u. per pound (or 42,500,000 B.t.u. per ton). Comparing bituminous coal at $3.00 per ton with oil fuel at $12 per ton, the former costs 9.4 cents per million B.t.u., compared with 28.2 cents per million B.t.u. for oil fuel. Since 28.2/9.4 = 3.00, the oil engine must be three times as efficient as the steam engine in order to bring the fuel cost down to the same value per brake horse-power-hour. A large modern steam engine or steam turbine should give out, in brake horse-power-hours, about 14 per cent. of the energy in the coal, under the conditions of service at sea. It is yet to be demonstrated that an oil engine can be built which will give out in brake horse-power-hours (3 × 14 =) 42 per cent. of the heat energy in the oil under the conditions of service at sea. At the present stage of development it would be venturesome to count on obtaining, under these conditions, an efficiency of more than (2 × 14 =) 28 per cent. Consequently, so long as fuel oil fuel costs more than (2 × $12 =) $8 per ton, as against coal at $3 per ton, the fuel cost will be greater in the case of the oil engine. This comparison is based on pre-war prices.

If, with producer plant, there can be developed a producer which will work satisfactorily with bituminous coal, the price for fuel would be the same in the two cases. Assuming an efficiency, say, of 21 per cent., from the coal to the shaft, as against 14 per cent. for a steam plant, then the fuel cost of the gas plant would be only two-thirds of that for the steam plant.

Should commercial success ultimately attend the efforts to develop an internal-combustion engine consuming coal dust in the cylinders, we shall

* See page 219 of the 1912 *Proceedings* of the Institution of Mechanical Engineers, where also will be found interesting particulars of many ships equipped with Diesel engines.

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inally have the result of high efficiency and cheap fuel. When supplied n the form of coal dust, 3 cents per million B.t.u. is a fair relative figure for he fuel cost. Assuming as the sea efficiency from fuel to shaft:

(a) 14 per cent. for boiler plant and steam engine or turbine,
(b) 28 per cent. for oil engine,
(c) 21 per cent. for producer plant and gas engine,
(d) 28 per cent. for coal-dust engine,

nd assuming for the price of fuel per million B.t.u.:

(a) 9.4 cents for coal for the steam-engine equipment,
(b) 28.2 cents for oil for the oil-engine equipment,
(c) 9.4 cents for coal for the gas-engine equipment,
(d) 3.0 cents for coal for the coal-dust engine equipment,

hen the costs per million B.t.u. given out at the shaft and per brake horse-power-hour given out at the shaft, work out as shown in Par.**30**.

30. Summary of Comparative Fuel Costs for Marine Prime Movers

	Fuel cost per million B.t.u. at shaft, cents	B.t.u. per h.p-hr.	Fuel cost per brake h.p-hr., cents
I. Steam plant	67	2,545	0.171
II. Oil-engine plant	101	2,545	0.257
III. Gas-engine plant	45	2,545	0.115
IV. Coal-dust engine plant	11	2,545	0.028

The attractively low fuel cost in the case of the coal-dust engine would be futile in marine propulsion unless attained with an engine of small weight and of low cost and upkeep. Since these results are for *comparative* purposes, the use of pre-war prices does not seriously affect the conclusions.

31. Low-speed, direct-connected turbines. Ever since the advent of the steam turbine into engineering work on land, there has been gradual but uninterrupted progress toward the employment of ever higher speeds. This progress has been accompanied by a great decrease in weight per horse-power and a very satisfactory decrease in steam consumption per brake horse-power-hour. In marine applications the difficulties encountered at an early date with respect to propeller efficiency, and the attainment of satisfactory operating characteristics of the propeller, imposed restrictions on the speeds employed. Consequently the early marine steam turbines were much heavier and less economical than land turbines for equivalent outputs.

The steam turbines of the "Mauretania" run at a speed of 188 r.p.m. and (exclusive of condensing plant) represent a weight of about 40 lb. per shaft horse-power. The steam consumption per shaft horse-power-hour during the full-speed trials was just over 12 lb.* Each of the four main turbines delivers about 17,000 s.h.p. Land turbines for three times this output can now be built with speeds of 1,800 r.p.m. and there is thus obtained, not only an enormous reduction in the weight per horse-power, but also a very satisfactory improvement in the steam consumption per shaft horse-power-hour.

32. Improved economy of high-speed turbines. By using 250 deg. fahr. of superheat, the firm of Messrs. Parsons obtained on a 750-r.p.m., 25-cycle, 25,000-kw. set of their construction, a steam consumption (guaranteed) of only 11 lb. per kilowatt-hour, which (allowing for an efficiency of 97 per cent. for the electric generator) is equivalent to 8.0 lb. per brake horse-power-hour from the steam turbine. High superheats can be used much more successfully in high-speed turbines, since with their relatively small diameters they are more rigid and more free from the difficulties consequent upon expansion than is the case with large, slow-speed, steam turbines. When tested with 220 deg. fahr. superheat, a pressure of 184 lb. per square inch at the boiler side of the pressure stop valve, a condenser pressure of 0.72 in., and a load of 9,000 brake-horse-power, a 40-cycle, 1,200-r.p.m.

* See p. 463 of *Engineering* for April 4, 1913.

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steam turbine in the Dunston-upon-Tyne power house of the Newcastle-upon-Tyne Electric Supply Co., was ascertained by Messrs. Mers and McLellan to have a steam consumption of 8.2 lb. per brake horse-power-hour. The turbine employed in this set was of the Curtis type and was built by the A. E. G. of Berlin.

Tests made on a 10,000-kw., 25-cycle, 1,500-r.p.m. generating set, constructed by the Gen. Elec. Co. and employing turbines of the Curtis type, showed a steam consumption of 12.7 lb. per kilowatt-hour when operating at 185 lb. gauge pressure, 100 deg. fahr. of superheat and 28 in. of vacuum. When reduced to terms of the pressure, superheat and vacuum of the Parsons 25,000 kw. set the consumption works out at 10.5 lb. per kw-hr. although the Curtis set is of only 10,000 kw. capacity as against 25,000 kw. for the Parsons machine.

In the case of a 1,500-r.p.m., 30,000-kw. set constructed by the Gen. Elec. Co. for the Chicago Edison Co., the steam consumption at a load of 25,000 kw. was guaranteed not to exceed 11 lb. per kilowatt-hour when operating at 220 lb. gauge pressure, 200 deg. fahr. superheat and 1 in. absolute back pressure.

33. High-speed, geared steam turbines. When it was first contended by Mr. Geo. Westinghouse and Sir Chas. Parsons that thousands of horse-power could be transmitted through toothed speed-reduction gearing of the double-helical type, with a loss of only 1.5 per cent. to 2.0 per cent., engineers were very sceptical. At present, however, many ships fitted with geared turbines are in service. In an editorial on page 610 of *Engineering* for Nov. 1, 1912, appears this statement regarding the efficiency of the toothed gear transmission: "The loss in transmission is only 2 per cent. as against 8 per cent. for electrical gear and from 10 per cent. to 14 per cent. for hydraulic gear."

The U. S. collier "Neptune" is equipped with Westinghouse geared turbines, the performance of which has been discussed by Lieutenant W. W. Smith in the 1912 *Journal* of the American Society of Naval Architects. For a vessel speed of 14 knots, the "Neptune's" propellers run at a speed of 135 r.p.m. and are driven through gearing with a ratio of 9.3 : 1. Each of the "Neptune's" two steam turbines is of some 3,000-h.p. capacity and runs at a speed of only 1,250 r.p.m. The "Neptune's" displacement is 20,000 tons.

34. Results of Trials of Sister Ships fitted with Geared Turbines and Triple-expansion Engines

	Cairnross	Cairngowan
Type of engine	Geared turbines	Triple-expansion
Revs. per min. (mean of 36 hours)	61.8	61.3
Coal per day	27.8 tons	32.7 tons
Indicated horse-power	—	1,700
Shaft horse-power	1,570	—
Ratio of shaft horse-power (Cairnross) to indicated horse-power (Cairngowan).	87.7 per cent.	—
Pounds of coal per indicated horse-power-hour, all purposes	Equiv. 1.54 lb.	1.70 lb.
Pounds of coal per shaft horse-power-hour, all purposes	1.65 lb.	Equiv. 1.94 lb.
Pressure at steam pipe in engine room	158 lb.	175 lb.
Vacuum	28.8 in.	26.3 in.

The machinery of the "Cairnross" is some 20 tons lighter than that of the "Cairngowan." See Par. 23.

35. Comparison of geared turbines and triple-expansion engines. The "Cairnross," a tramp steamer designed for a sea speed of 10 knots, is equipped with two steam turbines running at a speed of 1,700 r.p.m. and both geared with a ratio of 26.2 :1 to a single propeller with a speed of 65 r.p.m. The length between perpendiculars is 370 ft., and the breadth is 51 ft. On the trial run, the displacement was 9,950 tons; block coefficient, 0.779. The steamer fitted with triple-expansion engines, the "Cairngowan," is a sister ship to the "Cairnross," has practically the same dimensions, the

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ame propeller speed, and was loaded to the same displacement as the Cairnrose" during the 36-hr. trial. The results of the trials appear in Par. 34.

36. Alquist mechanical gearing. An interesting development in peed-reduction gearing is the Alquist mechanical gear for large powers, incorporating the feature of flexibility to the extent necessary to overcome the rave difficulties associated with rigid mechanical gears operating at high oth speeds.

37. Electrical transmission for marine propulsion. Although echanical speed-reduction gearing is quite appropriate for ships of low ower, making long journeys at a fairly constant speed, it is inferior in a umber of respects to the plan of interposing electric transmission between the rime-mover and the propeller. The electrical plan provides effectively for: 1) obtaining the desired speed reduction; (2) dispensing with any additional urbines for astern running. As to the first feature, the electrical method reatly excels the mechanical method in the respect that the ratio of reduction can be varied to any extent desired, thus permitting the operation of the hip economically at various speeds, while the prime-mover is preferably perated at substantially constant speed. Moreover, a greater ratio of peed-reduction is practicable with the electrical system than with mechanical gearing, and more favorable speeds can be adopted both for the steam urbine and for the propeller.

The second feature, the ability to reverse the ship by reversing the electric notors which drive the propellers, has not only the advantage of eliminating he additional turbines for astern running and thus lightening and cheapening he equipment and eliminating the considerable friction loss in the astern ection of the turbine, but there is the further advantage that in all manœuvring operations the full power of the main turbines is available, instead of the limited power of the astern turbines. Thus electrically-driven ships are characterised by their prompt and decisive manœuvring abilities.

38. Relative weight and efficiency of electrical gearing. For a given speed-ratio, the interposed electrical machinery would usually be heavier and more expensive than mechanical reduction gearing, but electrical gearing permits employing a *greater* speed reduction than is practicable with mechanical gearing. Consequently, with the electric drive, the prime-mover is lighter and more efficient than when the mechanical gearing is employed, and this saving is increased by the elimination of the astern turbines. It must be admitted, however, that the overall efficiency of the electrical machinery is rarely above 90 per cent. to 92 per cent. as compared with 98 per cent. efficiency of the mechanical gearing, but this difference is fully made up by the increased economy in the steam consumption of the prime-mover, because of its higher speed, and the improved efficiency of the propeller, because of its lower speed.

39. General conditions under which electric propulsion is best adapted. The general tendency was at first in favor of mechanical gearing for small ships, of low power, making long journeys at full speed, and electrical gear for large ships, and for ships requiring different speeds on different occasions, including those ships which frequently navigate inland waterways and crowded harbors and consequently require excellent manœuvring ability. But at present (1921) there is a strong tendency toward the extensive use of electric propulsion for a wide range of classes of ships. This is based partly upon experience to the effect that mechanical gearing has not come up to expectations in some respects and that experience with the electric drive has been very successful.

40. Special advantages of electrical gearing for ships operating at variable speeds. The most important reasons for operating ships electrically relate to the introduction of certain principles which, in land central stations for the generation of electrical energy, are recognized as having fundamental commercial importance. These principles can be well illustrated by considering the case of a battleship. Such a ship must be equipped with enough propulsive machinery to provide some stipulated maximum speed. This may require an aggregate capacity, say, of 32,000 h.p. If the ship is equipped with steam turbines direct-connected to the propellers, probably there would be four turbines, each of 8,000 h.p., connected to each individual propeller. But the ship will be driven at its full speed only a small portion of the time. Its cruising speed is only some six-tenths of the

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full speed, and it is at this lower speed that the ship is practically always driven. The power required to drive the ship at its cruising speed will be only of the order of 8,000 h.p. or less, as against the 32,000 h.p. aggregate capacity of the four turbines. Steam turbines become less efficient the lower the speed, and the lower the load. In this instance there would be four turbines running at only six-tenths of their full speed and only one-fourth of their full load. Under these conditions the steam consumption per horse-power-hour will be very much greater than at full speed and full load.

If the ship is arranged to be driven electrically, however, the general plan will be to employ a number of turbo-driven electric generators, of very high speed, situated in an engine room (or preferably in two independent engine rooms) located at a protected part of the ship. These generating sets will supply energy to electric motors which in turn drive the propellers. Under this plan, while all the generators and all the motors will be required when the ship is operating at full speed, three-quarters of the generating plant can be shut down when the ship is proceeding at cruising speed; and if there are two or three motors for each propeller, it will also be possible, at cruising speed, to switch out all but one of the motors for each propeller. By this means those generating sets which are in service will be running at their economical speed, and sufficiently near their full load to be highly efficient. The plan provides complete independence between the number of prime-movers and the number of propellers; consequently the number and size of prime-movers can be determined with due regard to the best economy.

41. Advantages of electric drive with internal-combustion engines. While internal-combustion engines are usually of moderate speed, and while, consequently, the speed-reduction feature is of less importance, the feature of operating the prime-movers at constant speed and of varying the number of prime-movers in service so that those in use shall be carrying their economical load, are equally valuable with internal-combustion engines. In fact, operation at constant speed is a factor of the very greatest importance in contributing to the success of large internal-combustion engines. There is the further important advantage that any occurrence rendering it necessary to repair a prime-mover during a voyage is usually of quite minor consequence and will not affect the progress of the voyage, since any particular engine is quite independent of any particular propeller.

In land central stations, an ensured continuity of service is obtained largely by virtue of having a number of independent generating sets. By the introduction on board ship of this feature of land practice, it becomes feasible at any time during the voyage to make such adjustments or repairs as are usually made in port on a ship having only one power unit for each propeller. It is an important advantage of the electrical method of propelling ships that it provides a great increase in flexibility in these directions over that which is otherwise practicable.

TYPES OF VESSELS FOR DIFFERENT SERVICE

42. Freight and tramp steamers. Representative vessels of this class range from 250 ft. length by 42 ft. beam and 14 ft. draught for canal routes up to some 420 ft. length by 52 ft. beam and 23 ft. draught for lake and ocean routes. The displacement ranges from some 5,000 tons for the former class, up to some 12,000 tons for the latter. The speed is of the order of some 8 to 12 knots; the power required is about 400 shaft h.p. for the smaller boats, ranging up to some 2,200 shaft h.p. for the larger.

As examples may be mentioned the "Cairngowan" (Par. **23**, **34**, and **35**) fitted with triple-expansion engines; the "Cairnross" (Par. **34** and **35**), fitted with geared turbines; the electrically propelled "Tynemount" (Par. **71** and **72**), with Diesel engines; the "Vespasian" (Par. **59**), with geared turbines and the "Selandia" (Par. **27**), with Diesel engines.

Such boats are usually provided with a single propeller, which shows preferably have a speed well below 100 r.p.m. In the largest vessels (420 ft. length) equipped with Diesel engines, two sets of engines and propellers will be customary.

43. Cross-channel boats. For modern cross-channel vessels for passenger transportation, speeds of the order of 20 to 23 knots are required. Their displacement is usually a matter of 1,500 to 2,500 tons and their engines should develop some 6,000 to 10,000 shaft h.p.

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44. Ocean liners. Although each year witnesses increases in the size f ocean liners, the most recent vessels are equipped for slightly lower speeds ıan the 26-knot "Mauretania" of the Cunard Line. This ship has an verall length of 790 ft., a breadth of 88 ft., a draught of 33 ft. 6 in., and a ısplacement of 38,000 tons. At full speed her turbines, of which there are ›ur, develop some 68,000 shaft h.p.

The Cunard liner "Berengaria" (formerly "Imperator"), has an overall :ngth of 920 ft. and an extreme breadth of 98 ft.; height, 100 ft. from keel › boat-deck and 246 ft. from keel to masthead; displacement, about 57,000 ›ns; propelled by four Parsons turbines, driving four screws of 16.5 ft. iameter, and four blades each. The total shaft output is about 62,000 h.p., orresponding to a draught of 35 ft. 6 in. and to a sea speed of some 22.5 nots; the corresponding propeller speed is 175 r.p.m. The coal bunkers ave a capacity for over 8,500 tons. Is now being altered to use oil fuel. 'ull complement of passengers, 4,000; total ship's company, 1,180.

The "Leviathan" (formerly "Vaterland"), has an overall length of 905 ft. nd a breadth of 100 ft.; the turbines develop 61,000 h.p. at about 180 r.p.m., orresponding to a sea speed of about 22 knots; accommodates 5,700 persons ncluding the crew.

The Cunard liner "Aquitania" has an overall length of 901 ft.; breadth, 97 ft.; and draught, 34 ft.; depth from keel to boat-deck is 92 ft.; propelled ›y steam turbines driving four screws; speed, 23.5 knots—corresponding o 60,000 h.p.; displacement, 50,000 tons.

45. Oil boats. Large oil-carrying vessels have capacity for 15,000 tons f oil. The "San Fraterno,"* when fully loaded with 15,700 tons of oil, ıas a draught of 28 ft.; length, 542 ft.; breadth, 66 ft. 6 in.; contract speed, 11½ knots (exceeded in trials); propelled by a quadruple-expansion engine; equipped for oil burning.

46. Ore and Grain Boats. Similar in general shape and capacity (Par. 45) are the ore carriers which transport cargoes of ore or grain between the Great Lake ports. The limitations of the depth of waterways through which they pass sometimes require a draught of less than 20 ft. On routes where such limitations do not hold, these vessels are often loaded to a draught of 24 ft. Their length is of the order of 600 ft.; beam, 58 ft; and moulded depth, 32 ft. They can accommodate a cargo of some 20,000 tons of ore or coal, or nearly half-a-million bushels of wheat, and can be loaded at the rate of 8,000 tons per hour. They are propelled at a speed of some 10.5 knots by a single screw, usually driven at about 120 r.p.m. by a triple-expansion engine of some 2,200 h.p.

47. Tug-boats are of course designed for towing service, mainly in sheltered waters. The three essential requirements are: (a) high speed when running free; (b) fair speed when towing; (c) high thrust or pulling effort at practically zero speed. If attention is paid first to the second requirement, the others will usually take care of themselves.

48. Battleships. The modern battleship has a length of from 550 to 600 ft., a breadth of some 90 ft. and a displacement of the order of 25,000 tons. A battleship is usually equipped for a maximum speed of about 21 knots; the cruising speed is about 12 to 14 knots. At maximum speed the engines are required to develop some 30,000 shaft h.p. There has recently been a tendency toward still larger battleships and the U. S. Navy now has on order some 23-knot, 60,000-h.p. electrically propelled battleships. Effectiveness in a battleship outweighs all questions of cost. A general movement is taking place toward the practice of burning oil fuel. By this plan, not only can a greater weight of fuel be stored in a given volume than with coal, but a ton of oil has a calorific value some 33 per cent. greater than a ton of coal. Consequently, with oil fuel, the radius of action is greatly increased. Furthermore, the use of oil fuel ameliorates the almost intolerable conditions in the stokehold.

49. Battle-cruisers. Ships of this class constitute a modern development. They differ from battleships in the respect of being equipped for much higher speeds. This entails a certain sacrifice in armament and in armouring. The United States Navy has on order several 180,000-h.p., 33.5-knot electrically propelled battle cruisers. As examples of battle-cruisers may be mentioned the following:

* *Shipbuilding and Shipping Record*, April 24, 1913, p. 149.

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The former German battle-cruisers "Moltke" and "Goeben." These ships had a length of 610 ft.; beam, 96.5 ft.; displacement, 23,000 tons; four propellers, driven by Parsons turbines aggregating 84,000 shaft h.p. The "Moltke" developed a speed of 28 knots, with the turbines running at 330 r.p.m.

The British battle-cruisers "Princess Royal" and "Lion" of 700-ft. length, 88-ft. 6-in. beam, and 26,000-ton displacement. Their turbines developed 70,000 shaft h.p. The "Princess Royal" displayed a speed of 33 knots, and the "Lion" a speed of 31 knots. The British battle-cruiser "Tiger" had 100,000 shaft h.p. (Par. 18).

50. Cruisers. Prior to the advent of the battle-cruiser, the term armored cruiser was associated with a ship of somewhat less displacement than a battleship, and a speed exceeding that of a battleship by only 3 or 4 knots. This is the class of ship now termed simply "cruiser." Ships of this class are about as long as a battleship, but have considerably less beam. As typical of such armored cruisers it may be stated that their length is some 500 to 550 ft.; beam, 70 to 78 ft.; displacement, 14,000 to 18,000 tons. Their speeds are of the order of 23 to 25 knots.

51. Light cruisers (often designated "scouts" or "scout-cruisers"). These vessels are small cruisers having a displacement of some 2,500 to 4,000 tons and a speed of some 24 to 26 knots. They require engines of from 19,000 to 20,000 shaft h.p. As examples in the United States Navy may be cited the engine-equipped "Birmingham," and the turbine-equipped "Salem" and "Chester." These three boats were 420 ft. long; displacement, about 3,750 tons with 450 tons of coal on board; coal bunker capacity, 1,250 tons. The speed was 24 knots and the power about 16,000 i.h.p.

The "Fearless," a typical British scout-cruiser, had the following proportions: length, 385 ft.; beam, 41 ft. 6 in.; displacement, 3,360 tons. She had turbines of an aggregate capacity of 18,000 shaft h.p. and developed a speed of 25 knots.

52. Colliers. Allusion has already been made to the collier "Neptune," in Par. **33**. The electrically-equipped collier, "Jupiter" is described in Par. **69** and **70**. A sister of these two ships was the "Cyclops" which was equipped with triple expansion engines. Some of the leading data of these ships have been taken from engineering publications and brought together in the following table (Par. **53**).

53. Data of Three Colliers of the United States Navy

	Cyclops	Neptune	Jupiter
Type of propulsive machinery...	Triple-expansion engines	Geared turbines	Turbo-electric
No. of engines	2	2	1
No. of propellers	2	2	2
Speed of engines	88 r.p.m.	1,250 r.p.m.	2000 r.p.m.
Speed of propellers	88 r.p.m.	135 r.p.m.	110 r.p.m.
Speed reduction ratio	1 : 1	9.3 : 1	18.1 : 1
Speed of vessel	14 knots	14 knots	14 knots
Displacement	20,000 tons	20,000 tons	20,000 tons
Cargo capacity	12,000 tons	12,000 tons	12,000 tons
Indicated horse-power at 14 knots	5,600	.....	.....
Steam consumption in lb. per shaft h.p.-hr.	14 lb. (estimated)	.....	11.2 lb. (tested)
Weight of driving machinery	280 tons	.....	156 tons
Speed during 48 hr. trial at sea..	14.6 knots	13.9 knots	See Par. 70
Corresponding output from engines.	6,705 i.h.p.	.....	for data of unofficial 48-hour trial
Corresponding speed of propellers	92 r.p.m.	.....	
Corresponding coal consumption for main engines only.	1.49 lb. per i.h.p. hr.	.....	

54. Torpedo-boat destroyers. Modern boats of this class have displacements ranging from 500 to 1,800 tons, and speeds of 28 to 36 knots. They burn oil fuel in order to secure a maximum radius of action. Torpedo-boat destroyers are now usually driven by steam turbines and are fitted with from two to four propellers. Owing to the high speed of which they must

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capable, their horse-power per ton of displacement is usually much higher an for vessels of any other class. Take for instance the British torpedo- at destroyer "Velox"; the displacement was only 440 tons, but at maxi- ım speed of 36.6 knots (see page 70 of Hobart's "Electric Propulsion of ips"), the vessel required some 12,000 shaft h.p. This small boat had ır propellers, and an engine capacity of about (12,000/440 =) 27 h.p. per ı of displacement, whereas scout cruisers have only some 4 h.p. per ton displacement. Battleships were until recently provided with only 1.0 h.p. 1.3 h.p. of engine capacity per ton of displacement. The *cruising* speed the "Velox" was only 11.3 knots, which required merely some 300 h.p. Thus a noteworthy characteristic of this class of ship is the great ratio of e power required at maximum speed to that required at cruising speed. the case of the "Velox" this ratio was 12,000 : 800 = 40 : 1.

ELECTRIC PROPULSION

55. Consequences of the self-contained feature in a ship-propul- n installation. There is one very important aspect of the proposition of ving a ship electrically, which should simplify its introduction in marine actice. Each ship represents an independent, self-contained proposition. ere is no particular need for, or advantage in, a rigid adherence to some one rticular system. There are usually several alternative methods of dealing th any engineering problem and it is often difficult to determine which the best. Generally, one can definitely discard several methods as less itable for some particular case, but there will usually remain two or three ıthods between which it is difficult to choose.

In undertaking the electrification of a railway, this may well constitute a eat embarrassment, since it is important to have standardisation and inter- angeability of rolling stock over extensive systems. But in the case of ship opulsion, comparisons of various types of engine equipment, of propeller signs and speeds, of locations of propellers, of number of propellers, of ıds of fuel, etc., are continually being made on ships of otherwise identical aracteristics. The rapid progress which is continually in evidence in ırine engineering is largely a consequence of this established policy. It asy to foresee that the application of electrical methods to ship propulsion ll be more readily accomplished (so far as it is demonstrated to realize the nomic advantages that are claimed for it), than has been the case with lway electrification.

The engineer's task will include determining upon a thoroughly appro- ate installation in each case. It will be entirely unnecessary for him to opt any other than the economically appropriate solution in any case, out consideration for uniformity with the machinery employed in some other se.

Various combinations of machinery for the electric propulsion of ships have en worked out, and some of them have crystallized into "systems." But re are many sound plans and principles of proved appropriateness which ve been employed in electric-power applications on land which are equally itled to be designated as "systems" appropriate for ship propulsion. It herefore not considered desirable to devote any space to detailed descrip- ns of "systems." The reader may care to refer to Chapters XIII to XVI, lusive, of Hobart's "Electric Propulsion of Ships" for descriptions of rious systems which have been proposed by Mavor, Emmet, Durtnall, y, Hobart, and others.

56. Turbines versus internal-combustion engines in electric opulsion. For anything over 4,000 h.p. it would appear that for elec- ally-driven ships the economic advantage will be greater when the steam bine is employed as prime-mover than when the oil engine is employed. the first place, the cost of steam turbines is only a matter of some 20 ıts per pound, as compared with some 50 cents per pound for oil engines. hese are pre-war figures.) Furthermore, the weight per horse-power for enginec of large output is several times the corresponding figure for steam bines of the same output. This handicap in cost is far from being off- by the cost of the steam-raising plant in the case of the steam turbine. reover, the fuel cost per brake horse-power-hour is at present greater for than for coal. In electric propulsion, the very highest turbine speeds may adopted, since in a self-contained plant such as that on board ship, the ticular periodicity employed is of no consequence.

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It had heretofore been usual for engineers to commit themselves to advocating either a geared-turbine drive or an electric drive. But this seems ill-advised. If the ratio of turbine speed to propeller speed is too great to be bridged economically and satisfactorily by double-helical gearing, on the one hand, or by an electric transmission on the other hand, then both should be used. For instance, for a 6,000-h.p. plant, either two 3,000-h.p. turbines could be employed or three 2,000-h.p. turbines, according to the requirements of the case. These turbines could be driven at 4,800 r.p.m., or even faster, and could supply a 60-r.p.m. propeller by first driving 600-r.p.m. generators through 8 : 1 gearing and then transmitting the power from these generators to 60-r.p.m. electric motors. This extreme case of a total speed-reduction of 80 : 1 has simply been taken to impress the viewpoint, and no special significance should be attached to the ratios selected for each of the two component speed reductions; these would be determined with due regard to the conditions in each particular case.

It should be realised that sacrifices are often made by keeping down to such a low turbine speed as 1,500 rev. per minute and that in each case the particular turbine speed should be adopted which leads to the best combination of low steam consumption and low weight and cost. But the mistake should not be made of sacrificing good characteristics in the electric generator by necessarily designing it for direct connection to the steam turbine. Similarly, for the electric motor, the design should be for a speed consistent with good electrical and mechanical characteristics and low weight and cost. If these are secured at a speed near that of the best propeller speed, then a compromise permitting the elimination of intermediate mechanical gearing may be appropriate; otherwise double-helical gearing, of 98.5 per cent. efficiency, should be interposed. As long as electric transmission constitutes one link in the chain, it is obviously a simple matter to provide a variable speed ratio and also to eliminate the astern turbines, thus securing excellent manœuvring characteristics.

Just as the steam turbine is at its best from 4,000 h.p. upward, so is the oil engine often appropriate from 3,000 h.p. downward, notwithstanding the high cost of oil fuel. In ships of such relatively small capacity as not to require more than 2,000 or 3,000 h.p., the elimination of steam-raising plant is of much importance. Furthermore, with the inclusion of the feature of electric transmission, the provision of a small oil-engine installation of two or three component units ensures ample reliability. The space and weight saved, partly in consequence of the elimination of the boiler room and partly in consequence of the fact that 0.4 of a ton of oil fuel is the equivalent (as regards the shaft output of the engine), of 1.0 ton of coal in a steam plant, will provide, in cargo vessels, sufficient increase in the cargo capacity to more than offset the considerably greater outlay for fuel at present prices. The range of capacities lying between 2,000 h.p. on the one hand and 4,000 n.p. on the other hand, constitutes a neutral zone where a study of the circumstances of each case will disclose some circumstance affording guidance to a correct decision.

57. Study of electric drive for the "Mauretania." In engineering estimates involving comparisons of alternatives, certain among which are untried, it is often necessary to discount liberally for the optimism of exploiters of systems. Making all due allowances of this kind, the following comparison is of interest and value. It is abstracted from a letter by Berge Ljungström written under date of April 12, 1912, and published at p. 538 of *Engineering* for April 19, 1912.

Ljungström has developed a turbine, both members of which revolve, and in opposite directions. This turbine is described in *Engineering* for April 12 and 19, 1912. In a 4,500-kw. turbo-generator set, the relative speed of the two parts of the turbine is 6,000 r.p.m. while the speed of the generator is only 3,000 r.p.m. Such a 4,500-kw., 6,000-r.p.m. turbo-generator weighs only 34 tons, or 11.5 lb. per horse-power. The total weight for the whole plant, with pumps, and with water in the condenser, is 65 tons, or 22 lb. per horse-power. The main dimensions are: Length, 23 ft. 7 in.; width, 6 ft. 7 in.; height, including condenser, 14 ft. 6 in. The 86-r.p.m. asynchronous motors with which Ljungström proposes to drive the propellers, would weigh 39 lb. per horse-power.

It is estimated that by installing on the "Mauretania" eight of these 4,500-kw. sets, and supplying energy from them to four motors (two motors on

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ich of two propeller shafts), the same vessel speed could be obtained by pplying only 45,500 shaft h.p. to the two 86-r.p.m. propellers as is now tained by supplying 69,000 h.p. to the four 188-r.p.m. propellers which e actually fitted to the ship.

The calculations in Ljungström's comparison are given in tabular form in s letter and include cost estimates.

58. Study of electric drive for the destroyer "Hugin." Ljungström s also worked out estimates for an electric drive for the 348-ton Swedish estroyer "Hugin," which is now equipped with Curtis turbines of 10,400 aft h.p., 850 r.p.m., and direct-connected to the propeller shafts. The rresponding vessel-speed is 31.2 knots. By substituting a Ljungström rbo-electric transmission, it is estimated that the propelling power would reduced to 6,500 shaft h.p. and the coal consumption to 42 per cent. of present value; the weight would be decreased by 75 tons and the floor ace by 33 per cent. This turbo-electric alternative comprises three turbo-nerators driving electric motors at 500 r.p.m. normal speed.

59. Study of electric drive for the cargo boat "Vespasian." Ljungström has also described an electric transmission which he proposed for e cargo boat "Vespasian." He states that "the electric motors, intended r 100 periods, are two in number and *geared* to the shaft." On p. 106 of obart's "The Electric Propulsion of Ships," this same plan was earlier dvocated in the following words: "The disabilities of low-speed induc-on motors may be escaped and advantage may be taken of their good ualities by arranging that high-speed motors shall drive the propeller-shafts low speeds through double-helical speed-reduction gearing. The pinions two (or even more) motors could be arranged to gear with a single low-eed gear-wheel on the propeller shaft, quite analogously to the way in which vo steam turbines drove the 'Vespasian's' shaft in the tests made by Parsons. sually the 2 per cent. loss in the gearing would be largely offset by the gher efficiency of the high-speed induction motor, and the weight and st of the gearing would be partly offset by the lesser weight and cost of gh-speed as compared with low-speed induction motors. The difficulties sociated with finding space in ships for large diameters are also eliminated this plan."

60. W. L. R. Emmet on electric propulsion. Mr. W. L. R. Emmet s read papers on electric ship propulsion before various engineering socie-s. References to these papers are given in the bibliography (Par. 79). 1909 Mr. Emmet designed an electrical equipment for the battleship Wyoming" and a proposal embodying these designs was made to the Govern-ent. In the spring of 1913 Mr. Emmet submitted a design which applied a case like that of the "Pennsylvania." The estimates as to the results this equipment as compared with those accomplished by the equipment the "Pennsylvania" are shown by the following table:

	R.P.M. at 21 knots	H.P. required at 21 knots	Pounds of steam per hour, turbines alone, 21 knots	Pounds of steam per hour, turbines alone, 15 knots	Weight of driving machinery in tons
Turbine drive with geared cruising turbines as adopted.	222	31,700	374,000	106,000	749
Turbo-electric drive.....	160	29,200	205,000	91,000	598

Mr. Emmet stated in 1913* that if in 1909 his first design for a warship had been accepted by the Navy Department, the vessel produced would have been very greatly superior in respect to economy reliability, weight, simplicity, and cruising radius, to any ship afloat in 1913.

*In a paper read on Dec. 11, 1913, before the Society of Naval Architects and Marine Engineers.

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61. Mavor system of electric propulsion; "spinner" motor. In a paper entitled "Electric Propulsion of Ships, with Note on Screw Propellers," read before the Institute of Engineers and Shipbuilders in Scotland, on Feb. 18, 1908, Mr. Henry A. Mavor describes an electric drive for a 17,000-brake h.p. ship with three propellers and a maximum vessel speed of 21 knots. Power would be provided by two turbo-generators from which three induction motors are driven. The motors are of a type which he designates as "spinner" motors and from which he obtains three efficient speeds.

On Dec. 7, 1909, Mr. Mavor read another paper in London (see p. 134 of Vol. 179 of *Proc.* Inst. Civil Engineers), in which he developed further plans employing the "spinner" type of motor. These studies constituted important steps in the history of ships propulsion, and the papers should be consulted.

62. Study of electric drive for the cargo boat "Frieda." Among other interesting projects for turbo-electric drives which have been worked out by Mr. Mavor (Par. 61) may be mentioned one described in a paper which he read at the Portsmouth meeting of the British Association in September, 1911, and published in the *Electrician* for Sept. 8, 1911. This case related to the "Frieda," a 300-ft., single-screw vessel for the transport of bulk freights between the Gulf of Mexico and New York City. The vessel was for carrying a dead weight of 5,000 tons at a mean loaded speed of 12 knots at sea. The turbo-electric generator was to run at 3,000 r.p.m. The generator provided three-phase, 50-cycle, alternating current to a 1,900-brake. h.p. induction motor which drove the propeller at about 58 r.p.m. It was estimated that such an installation would cost less and weigh less than the normal equipment, and that the saving in coal would amount to 10 tons per day. Owing to various reasons, one of which related to the skepticism of the owners, this vessel was finally equipped with reciprocating engines instead of with the proposed turbo-electric drive.

63. Reference to descriptions of other proposals for electric propulsion. Various other turbo-electric drives which have been proposed for ship propulsion are described in Hobart's "Electric Propulsion of Ships," D. Van Nostrand Co., New York, 1912.

64. Oil-electric projects for ship propulsion. Mr. Mavor* has described several plans employing Diesel engines driving electric generators which, in turn, drive a motor or motors direct-connected to the propeller. He has also described the plans† proposed for driving a 245-ft. Canadian canal-type tank barge and employing three Diesel engines, each capable of developing 200 shaft h.p., direct-connected to alternating-current generators. It was proposed that the energy from one or all of these sets should supply one or all of three separate windings of a squirrel-cage inductor motor keyed to the main propelling shaft and operating a single slow-turning screw.

EXAMPLES OF ELECTRICALLY PROPELLED SHIPS

65. Russian tank vessel. In 1903 the Société Nobel Freres, of Petrograd, constructed an oil-tank ship of 1,100 tons displacement and fitted with electric transmission gear. The vessel was employed on the Volga and in the Caspian Sea. She was equipped with three Diesel engines with an aggregate capacity of about 360 h.p. direct-connected to continuous-current generators which in turn supplied energy to three motors, on the three propeller shafts, respectively. The vessel had a speed of some 7 to 8 knots. The control was arranged from the bridge.

66. The Chicago fire boats "Graeme Stewart" and "Joseph Medill." The electric equipments for these boats were designed in 1908 by Mr. W. L. R. Emmet and built by the General Electric Co. of Schenectady. Mr. Emmet describes these installations as follows:‡

"Each of these boats is equipped with two turbines having a capacity of about 660 h.p. each, and operating at a speed of 1,700 r.p.m. One end of the shaft of each of these turbines is connected to a large centrifugal fire pump and the other end is connected to a 200-kw. direct-current generator. The boats are propelled by twin screws and the speed and direction of each motor is controlled by manipulation of the field of the generator which drives it."

* See page 134, Vol. 179, of *Proc.* Inst. Civil Engrs.
† See *Electrician* for Sept. 8, 1911.
‡ In a brochure issued in 1913 by the General Electric Co.

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These Chicago fire boats have a length of 120 ft. and are of 26 ft. beam and 10 ft. draught. On page 389 of *Engineering* for Sept. 20, 1912, will be found scale drawings of the general arrangement of the machinery in these boats.

Mr. Emmet has made tests directed toward studying the propeller characteristics of these boats and has published the results in a paper presented in New York in November, 1911, before the Society of Naval Architects and Marine Engineers.

67. The "Electric Arc." In 1910 and 1911 Mr. Henry A. Mavor equipped with electric gearing a 50-ft. steel-built vessel, and subjected it to a series of tests. This boat, the "Electric Arc," was launched in February, 1911. See description in Par. **68**.

68. The "Multiple" squirrel-cage motor. The generator supplied three-phase current to a squirrel-cage induction motor, also of a type invented by Mr. Mavor (British Patent No. 12,917 of 1909) and to which he applies the designation of "multiple" motor. This motor drives the propeller at one or other of two speeds, in accordance with the following plan:

The stator is provided with two independent windings for two different pole numbers. At its normal speed, the generator provides periodicities which bear to one another the ratio of these two different pole numbers. By connecting the winding of higher pole number to the supply of lower periodicity an efficient running speed of low value is obtained. For higher speed and power, the winding of higher pole number is transferred to the supply of higher periodicity and the winding of lower pole number, which was idle for the lower speed and power, is connected to the supply of lower periodicity. Consequently, at full speed and power, both sources of supply and both motor windings are fully utilized, and cooperate in driving the propeller. With this "multiple" motor it is thus possible to integrate in a single motor the power from several prime movers and also to obtain two or more efficient speeds without resorting to a motor with moving contacts.

69. The United States Collier "Jupiter." Certain leading data of this vessel have already been given (Par. **53**) and an illustrated description appeared in an article entitled "Electrical Equipment for the Propulsion of the U. S. Collier Jupiter," by Mr. Eskil Berg at page 490 of the *General Electrical Review* for August, 1912. The "Jupiter," a vessel of 20,000 tons displacement and designed to carry about 12,000 tons of coal and oil, was built at the Mare Island Navy Yard. The contract for the equipment was awarded to the General Electric Co., in June, 1911. The machinery was designed by, and constructed under the direction of, Mr. W. L. R. Emmet. The contract price of the electrical propelling machinery was stated in the article in the *General Electrical Review*, to be $13.75 per horsepower. The turbo-electrical propelling machinery comprises a 9-stage, 2,000-r.p.m. Curtis turbine driving a 2-pole, three-phase, 2,300-volt, 33⅓-cycle, 5,500-kv-a. generator. The two 36-pole, 110-r.p.m. induction motors each have a normal rating of 2,750 h.p. The rotors are provided with three-phase windings leading to slip rings. By means of these slip rings, the rotor current, at starting, reversing and manœuvring, is carried to water-cooled resistors which are short-circuited when the ship is proceeding normally. The heat is removed from the active material of these resistors by the circulation of sea water through them.

An interesting feature of the arrangement of the machinery relates to the provision of sheet-metal ducts so connected to the air outlets from the generator and motors as to lead the heated air to the suction of the fire-room blowers, thus avoiding needless heating of the engine room.

70. Performance of the "Jupiter." The "Jupiter" was put in commission September 15, 1913. After a period of preliminary trials in San Francisco Bay and at sea, the ship was docked. After cleaning her bottom, a set of standardisation runs and a 48-hour unofficial trial were made. On the 48-hr. trial the ship averaged 14.78 knots. The average power delivered by the generator was 5,000 kw., corresponding to about 6,300 h.p., delivered from the electric motors to the propellers. The average revolutions of the propellers were 115. The "Cyclops" (see Par. **53**) in her official 48-hour run made 14.61 knots with an average of 6,700 i.h.p. These particulars are taken from Mr. Emmet's paper read on Dec. 11, 1913, before the Society of Naval Architects and Marine Engineers.

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71. The "Tynemount." Messrs. Swan, Hunter and Wigham Richardson built to the order of the Electric Marine Propulsion Company of Glasgow, a canal-type tank barge for service on the Canadian lakes and through the Welland Canal. The vessel was built for operation by the Montreal Transportation Company, and was designed and fitted under the supervision of Messrs. John Reid and Henry A. Mavor. The "Tynemount" was described, with drawings, in a paper by these gentlemen read in June, 1913, before the Institution of Naval Architects and entitled "A Case for Electric Propulsion." Owing to disappointments with the Diesel engines, these and the electric equipment were subsequently replaced by reciprocating steam engines. But the project is nevertheless of much interest as being one of the first instances of the installation of the electric drive. The power equipment consisted of two four-stroke-cycle, 400-r.p.m., 6-cylinder Diesel engines, each direct-connected to a three-phase 235-kv.-a., 500-volt generator. These two generators were wound respectively with 6 and 5 poles and thus constituted sources of different periodicity, the one supplying 20 cycles per second and the other 26.6 cycles per second. An exciter was fitted on an extension of the shaft of each generator. Each exciter gave normally about 30 amp. at 100 volts and was capable of supplying a considerable overload. The propeller was driven by a "multiple" motor of the type invented by Mr. Mavor and already described (Par. 66). This motor was of the squirrel-cage induction type and was provided with two stator windings for 30 and 40 poles respectively. At the vessel's normal speed the power of the two Diesel engines was integrated at this motor, the 20-cycle supply being absorbed in the 30-pole winding and the 26.6 cycle supply in the 40-pole winding. Under these conditions the synchronous speed was 80 r.p.m. Allowing for slip in the rotor of this motor the propeller speed was about 78 r.p.m. By changing the 40-pole winding to the 20-cycle generator and leaving the 30-pole winding of the motor and the 26.6-cycle generator out of circuit, the speed was lowered to 75 per cent. of full speed, *i.e.*, to some 58 r.p.m. The 26.6-cycle set could then be shut down thus leaving the 20-cycle set alone to propel the ship and consequently providing as good economy at this low speed and load as at the higher speed and load. The vessel was designed to carry about 2,400 tons dead weight of cargo, fuel, fresh water and stores on a 14-ft. mean draught in fresh water. On p. 413 of Engineering for Sept. 27, 1912, the cost of the Tynemount is given as £30,000 ($150,000).

The dimensions of the ship and of her propeller were determined by the dimensions of the canal locks through which she was to pass. The system adopted permitted of increasing the carrying capacity to 250 tons more than would have been practicable with steam equipment. This saving was a consequence of:

(a) The absence of boilers and the consequent reduction in space and weight of machinery.

(b) The great difference in the heat value of the fuel and the efficiency with which it was used, so that the bunker capacity could be materially reduced.

The "Tynemount" is fully described and illustrated in an article published at p. 381 of *The Engineer* for Oct. 10, 1913.

The "Tynemount" was 250 ft. long, of 42 ft. beam and had a displacement of some 3,400 tons at 14 ft. draught in fresh water. She was designed for a speed of some 8 knots.

72. Performance of the "Tynemount." On the 17th of September, 1913, the Tynemount made her first trip, and her performance was tested at sea over a measured mile. She was also reversed many times and it was ascertained that only some 15 to 18 sec. were required to bring the propeller from full speed ahead to full speed astern or *vice versa*. This is an interesting demonstration of the excellent capabilities of properly designed squirrel-cage induction motors for work where considerable starting and accelerating torque is required. The design of the squirrel cage comprised the feature that the slots were exceedingly deep and narrow in order to take advantage of the "Field" effect which acts to impart high resistance characteristics to the rotor at starting. The high resistance characteristics automatically merge into low resistance characteristics as the motor speed increases. Consequently, the slip and losses are low at full speed, whereas, with the ordinary construction employing high resistance rotor bars of the usual proportions, the slip and losses and heating would be undesirably high during normal running.

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73. The "Mjölner," completed in 1914 and employed in Swedish coastrise service, is 225 ft. in length, 36 ft. beam, full-load draft 14.8 ft., displacement 2,270 metric tons and gross tonnage 976. At full speed of 11 knots, he develops 900 shaft h.p. The power plant comprises two 400-kw., 3,600-.p.m. Ljungström turbo-generators delivering 60-cycle, 500-volt, three-hase current. The propeller is driven at 90 r.p.m. from the low-speed heel of 10 to 1 gearing, from two 900-r.p.m. induction motors. Steam is upplied to the turbines at 218 lb. pressure and with 235 deg. fanr. of supereat. The "Mimer," a sister ship fitted with ordinary reciprocating engines, nd operated without superheat, was tested in service in comparison with he "Mjölner." The latter was shown to have a 42 per cent. lower coal onsumption. Several electrically driven ships of the "Mjölner" type and ize are at present in service.

74. The "Wulsty Castle," a cargo boat of the Chamber's Castle Line onstructed at Sunderland, England, is 356 ft. in length, 48 ft. beam, and 4 ft. draft when loaded with 6,000 tons of cargo. Her propelling machinery, uilt by the Brush Electrical Engineering Co. of Loughborough, comprises wo Ljungström 60-cycle, 3,600-r.p.m. turbo-alternators, each having a ating of 625 kw., the total output of a 1250 kw. being delivered to two 714-.p.m., 785-h.p. induction motors of the wound-rotor type. The single crew runs at about 75 r.p.m. for the ship's full speed of 10 knots, being gear riven with a ratio of 9.4 to 1. The conditions of steam pressure and superieat are the same as for the "Mjölner." The turbine speed is maintained onstant, and varying speeds of the ship are obtained by liquid resistors in he rotor circuits. It is stated that in bad weather at sea, the load continuilly fluctuates from 25 per cent. to 150 per cent. of normal full-load value.

75. The "New Mexico," a battleship of the United States Navy in ervice since the summer of 1918, has a displacement of 32,000 tons, a length of 620 ft. and beam of 96 ft. At full speed of 21 knots, the output from her wo Curtis turbo-generators is 30,000 kv.-a., the corresponding input to he four propellers being about 31,200 h.p. The corresponding screw speed s 167 r.p.m. The generators are two-pole and at 2,100 r.p.m., maximum peed, deliver a periodicity of 35 cycles. The windings are two-phase, for 1,240 volts or 3,000 volts according to the connections. The stators of the our motors are fitted with windings which can be connected for either 24 or 36 poles, giving synchronous speeds of either 175 or 117 r.p.m.; intermediate speeds are obtained by governing the turbine speed. The rotors are of the double-squirrel-cage design. The weight of the two main turbine-generator units, four main motors, switchgear and controlling machinery aggregated 530 tons and the contract price (including engine-room auxiliaries), was $431,000. The estimated weight of the Parsons turbine equipment originally contemplated for the "New Mexico" was 653 tons. It was estimated by the Navy engineers that a saving of $200,000 was made by adopting the electric drive. The steam consumption guarantees, which cover the total amount of steam for the main generating sets and the auxiliaries before mentioned, at a steam pressure of 250 lb. at the throttle, were as follows: at 10 knots, 14.6 lb. per shaft h.p.-hr.; at 15 knots, 11.4 lb.; at 19 knots, 11.1 lb.; at 21 knots, 11.9 lb.

The following table by Mr. Eskil Berg compares the water rates of the battleships "Florida" and "Utah," which are equipped with Parsons turbines, the battleship "Delaware" which is fitted with reciprocating engines, and the battleship "New Mexico" which is fitted with the Curtis turbo-electric drive.

	Propeller speed in r.p.m.	Water rate in pounds per effective h.p.-hr.		
		12 knots	19 knots	21 knots
Florida	328	31.8	24.0	23.0
Utah	323	28.7	20.3	21.0
Delaware	122	22.0	18.7	21.0
New Mexico	175	17.3	15.0	16.4

Each of the new battleships, "California," "Maryland" and "West Virginia," will be electrically propelled, having two generating units with a total of 28,000 h.p. output of similar type.

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76. The "Tennessee," a battleship of the U. S. Navy, is equipped with two Westinghouse turbo-generators and four propelling motors. At the ship's full speed of 21 knots, the generators deliver 25,500 kw. to the four motors; each motor will then deliver 8,375 h.p. to its propeller. The steam conditions are 250 lb. pressure per sq. in., 50 deg. of superheat and a 28.5-in. vacuum. At normal turbine speed of about 2,100 r.p.m., the periodicity is 35 cycles, as in the case of the "New Mexico." The generators are wound 3-phase, for 3,400 volts. The motors each have two separate stator windings for 24 and 36 poles. With 24-pole operation the rotors are equivalent to "wound" rotors and are started with liquid resistors. For 36-pole operation the rotors have the equivalent of internally short-circuited windings. Based on 250-lb. steam pressure, no superheat and 60-deg. circulating water, the guarantees are as follows: at 10 knots, 15.45 in. per shaft h.p.-hr.; at 15 knots, 12.1 lb.; at 19 knots, 11.65 lb.; at 21 knots, 11.9 lb. Several similar battleships will be equipped with same type of electric drive.

77. The "Powhatan," of the West Coast Steamship Co., is a merchant ship of the type to which electric drive is being applied in large numbers. This vessel is designed for a speed of 16.5 knots. Her length and beam are respectively 310 ft. and 40 ft. The generating equipment consists of a 3,000-r.p.m., 50-cycle, 1,150-volt, 2,350-kw. turbo-generator. The screw is driven from a 60-pole, 3,000-h.p., 100-r.p.m. motor.

78. The "Mariner," which is typical of thousands of fishing trawlers, is the first of this type to be equipped with electric drive. Her two Diesel engines are coupled to two 6-pole, 165-kw., 350-r.p.m., 125-volt, direct-current generators. At the full speed of some 10 knots, the two generators are connected in series and supply 330 kw. at 250 volts to an 8-pole, 400-h.p. 250-volt motor which drives the screw at some 200 r.p.m. For low speeds it is only necessary to operate a single generating set, delivering current at 125 volts to the motor. The "Mariner" has been in successful service since she was launched in December, 1919. Her length is 150 ft., beam 24 ft., draft about 12 ft. and displacement 500 tons.

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SECTION 19

ELECTROCHEMISTRY

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† Deceased.

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SECTION 19

ELECTROCHEMISTRY

INTRODUCTION

1. Definition. Electrochemistry deals with the production of electrical energy from chemical energy (primary batteries, storage batteries) and with the reverse problem, namely, the production of chemical effects by electrical means. Only the latter problem, however, will be covered in this section.

2. Chemical equations. The briefest way to make a quantitative statement of an electrochemical fact is by means of a chemical equation. If the chemical equation of a certain reaction or process is given, it is possible to derive a great many conclusions from it with the aid of certain sets of constants, such as atomic weights, formation energies, the constants of the gas laws, of Faraday's law, etc. We will first give a concise summary of the different ways in which a chemical equation may be interpreted; this will involve summing up the fundamental principles of physical chemistry and electrochemistry. Interpreting a chemical equation in different ways means looking at the reaction from different standpoints. This is of greatest importance for any electrochemical proposition, and it is not generally appreciated, especially by electrical engineers, how manifold the points of view are for considering a chemical problem.

3. Electrochemical processes. This will be followed by a concise summary of those electrochemical processes which have attained industrial importance. For the purpose of convenience a division into the following **three classes** will be made: Electric furnace processes; electrolytic processes and processes involving electric discharges through gases, although a sharp separation of these three classes cannot be made in reality. Each class will be introduced by a summary of the principles governing the processes in that class. In giving references to available literature, the aim has been to refer to those articles and papers which contain the latest and fullest technical information and which are most easily accessible to American readers.[1]

INTERPRETATION OF CHEMICAL EQUATIONS

4. A gram-atom is that number of grams of an element which is equal to the atomic weight. A kilogram-atom is the same number of kilograms, etc. A **gram-molecule** (or "mol") is that number of grams of a substance which is equal to the molecular weight. It is very important to always clearly distinguish between atoms and molecules; thus a gram-atom of chlorine = Cl = 35.45 g., while a gram-molecule or a mol of chlorine = Cl_2 = 70.90 g. A gram-atom of oxygen = O = 16 g.; but a gram-molecule of oxygen = O_2 = 32 g., and a gram-molecule of osone = O_3 = 48 g. A kilogram-molecule of calcium carbide = CaC_2 = 64.1 kg.

5. Interpretation of chemical equations. The equation of the reaction between burnt lime and ground coke in the production of calcium carbide in the electric furnace is

$$\underset{56.1}{CaO} + \underset{36}{C_2} = \underset{64.1}{CaC_2} + \underset{28}{CO}. \quad (1)$$

[1] For further literature reference must be had to the transactions of the three electrochemical societies, namely: the *Transactions* of the American Electrochemical Society, the *Transactions* of the (British) Faraday Society, and the *Zeitschrift für Elektrochemie*, which is the organ of the (German) Bunsen Society. The principal independent publications specialising in electrochemistry are *Chemical and Metallurgical Engineering* (New York), *Elektrochemische Zeitschrift* (Berlin), *Journal du Four Electrique et de l'Electrolyse* (Paris), *La Houille Blanche* (Lyons and Grenoble).

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The figures placed below the chemical symbols are the molecular weights. he equation states that when 56.1 kg. of burned lime combine with 36 kg. coke, there are formed 64.1 kg. of calcium carbide and 28 kg. of carbon onoxide. Instead of kilogram, we could use just as well any other unit of eight (pound, ton, etc.), since the chemical equation gives only the *relative* weights of combination. The table of atomic weights is given in Sec. 4.

ELATION BETWEEN VOLUME, PRESSURE AND TEMPERATURE IN GASES

6. Avogadro's law. If any of those substances taking part in a reaction ; a certain temperature is in the gaseous state and we know the pressure, e can find its volume directly from the equation of the reaction; or if we now its volume we can directly find the pressure. According to Avogadro's ile, equal numbers of molecules of different gases fill equal volumes under ie same conditions of temperature and pressure. One gram-molecule of ny gas (for instance, 2 g. hydrogen, H_2, or 32 g. oxygen, O_2) at atmoseheric pressure (760 mm. mercury) and at a temperature of 0 deg. cent. lls 22.42 liters. One kilogram-molecule fills 22.42 cu. m.

Example: The 28 kg. of carbon monoxide gas set free in the formation of 4.1 kg. of calcium carbide according to the above equation (Eq. 1, ar. 8) are 1 kilogram-molecule and will therefore fill 22.42 cu. m. when rought to a temperature of 0 deg. cent. and to a pressure of 1 atmosphere.

7. Boyle-Mariotte-Gay-Lussac law. To calculate the volume for ther temperatures and pressures, the Boyle-Mariotte-Gay-Lussac law is to e applied, according to which

$$p\,v = R\,T = R \times (273 + \text{deg. cent.}) \qquad (2)$$

In this equation p is the pressure, v the volume; hence $p\,v$ the work done i the expansion of the gas. T is the absolute temperature = temperature i degrees centigrade plus 273. R is the gas constant. If we measure the ressure in atmospheres and the volume in liters, then Avogadro's rule :ates that for $p = 1$ and $T = 273$, 1 gram-molecule of gas fills the volume $= 22.42$, hence $R = 22.42/273 = 0.0821$. Hence for 1 gram-molecule, f we give

$p\,v$ in liter-atmospheres, $R = 0.0821$
$p\,v$ in kilogram-meters, $R = 0.848$
$p\,v$ in gram-calories, $R = 1.987$.

'or n gram-molecules the value of $p\,v$ is n times the value found from the bove equation.

Example: If we electrolyze a dilute acid or alkaline solution for the urpose of producing oxygen and hydrogen gas and if we wish to use the ydrogen, for instance, for filling a balloon, then the main reaction is simply he decomposition of water.

$$H_2O = H_2 + O; \qquad (3)$$

.e., 1 kilogram-molecule or 18 kg. H_2O are decomposed into 1 kilo-ram-molecule or 2 kg. H, occupying 22,420 liters at 0 deg. cent. and tmospheric pressure, and 0.5 kilogram-molecule or 16 kg. O, occupy-ng 11,210 liters under the same conditions of temperature and pressure. If he hydrogen gas is contained in a balloon which is to rise in the atmosphere, t will be under atmospheric pressure, and the hydrogen produced from 18 ilograms of water, will under this condition fill 22,420 liters at 0 deg. cent. f the temperature is higher, for instance t deg. cent., and the pressure less, or instance, $760 - x$ mm. of mercury (when the balloon rises), then the volume n liters $= \dfrac{22{,}420 \times 760 \times (273 + t)}{(760 - x) \times 273}$.

8. Units employed. The calculation is quite as simple for English nits instead of metric units. As J. W. Richards[1] has remarked, the same umerical factor can be used as in the metric system. This coincidence is lue to the fact that there is practically the same relation between an ounce av.) and a kilogram, as between a cubic foot and a cubic meter, the differnce being negligible. Hence 1 ounce-molecule of a gas (for instance 28 z. carbon monoxide) at 0 deg. cent. and 1 atmosphere fills 22.42 cu. ft.

9. Gas mixtures. If we have a mixture of different gases in the same pace, two different views are *a priori* possible. Instead of $p\,v = R\,T$ we

[1] Richards, J. W. "Metallurgical Calculations," 1912; Vol. I, p. 3.

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might write in this case $p(v_1+v_2+v_3+\ldots)=RT$, assuming that all the gases have the same pressure p, but each occupies only a certain part of the total volume (the same as it would occupy alone under the same conditions of temperature and pressure); v_1 v_2 v_3 . . being the **partial volumes** of the different gases 1, 2, 3, . . and their sum being the volume of the mixture; or we may write

$$(p_1+p_2+p_3+\ldots)v=RT, \qquad (6)$$

assuming that every one of the gases fills the total volume v of the mixture but that each exerts only part of the total pressure; p_1 p_2 p_3 . . being the **partial pressures.**

10. The composition of a gas mixture may be defined either by the ratio of the weights of the constituent gases (or in per cents. of weight) or by the ratio of the partial pressures or the ratio of partial volumes (or in per cents. of volume). For instance, if atmospheric air is a mixture of 23.1 per cent. by weight of oxygen and 76.9 per cent. by weight of nitrogen, the partial volumes are found as follows: In 100 g. of air are 23.1 g. or 0.72 gram-molecule of oxygen and 76.9 g. or 2.74 gram-molecules of nitrogen. At atmospheric pressure and 0 deg. cent. the partial volume of the oxygen is therefore $0.72\times22.42=16.2$ liters, the partial volume of the nitrogen is $2.74\times22.42=61.5$ liters. The total volume of air is 77.7 liters. Hence the per cents. by volume are 20.8 per cent. of oxygen and 79.2 per cent. of nitrogen. In an analogous way the partial pressures may be calculated.

11. Hypothesis of partial pressures vs. partial volumes. For many calculations the hypothesis of partial volumes is as good as that of partial pressures but the latter is the only one strictly tenable. For instance, we have steam in the atmosphere at 0 deg cent., although we know, that at atmospheric pressure and 0 deg. cent., water could not exist in gas form. Therefore we must conclude that in the atmosphere steam is under less than atmospheric pressure; this leads directly to the conception of partial pressure. Finally it must be added that the above rules are strictly true only for ideal gases.

RELATION BETWEEN OSMOTIC PRESSURE, CONCENTRATION AND TEMPERATURE IN SOLUTIONS

12. Analogy between gaseous and osmotic pressures. On account of the analogy between the laws of gaseous pressure and of osmotic pressure in dilute solutions we can apply directly the results of Par. 6 to 11 to dilute solutions; *i.e.*, if one of the products of a chemical reaction appears in aqueous solution of given volume and if we know that the law of osmotic pressure are strictly valid for the solution in question, then we can state at once the osmotic pressure from the equation.

13. Osmotic pressure. If an n per cent. aqueous solution of a non-electrolyte is placed in a closed vessel, the walls of which are semi-permeable, *i.e.*, permit water only to pass through, but not the solute, and if we place this vessel in a larger reservoir filled with water, then the solution in the smaller vessel attracts water from the outside until a certain pressure is produced within the vessel. This pressure is called the osmotic pressure and its value in atmospheres is $0.0821\times$number of gram-molecules per liter$\times$absolute temperature (Van't Hoff). This is the same equation as in Par. 7 with the exception that instead of the volume v (the number of liters which are filled by 1 gram-molecule) we use here the reciprocal value, $c=1/v$ which is the concentration in gram-molecules per liter, so that the equation $pv=RT$ is written in this case $p=RcT$.

Example. As an example we want to find the osmotic pressure of a 7 per cent. sugar solution at 7 deg. cent. The molecular weight of sugar $=342$; 1 liter of a 1 per cent. solution contains 0.01 kilogram or 10 grams or 10/342 gram-molecules of sugar. Hence $c=10/342$, $T=280$, and the osmotic pressure $=\dfrac{0.0821\times10\times280}{342}=\dfrac{2}{3}$ atmosphere (Pfeffer).

14. Explanation of osmotic pressure. We may describe the general phenomenon in another way by saying that the pure water outside attracts the solute inside, and since the latter cannot pass outside it presses against the walls. Thus the osmotic pressure may be pictured as the pressure which is produced by the solute inside the vessel due to its inability to pass

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ly to the outside—just as a gas inside a reservoir exerts a pressure on walls, because it cannot follow its tendency to pass outward. More- r, for the osmotic pressure and the gaseous pressure the same numerical holds true as shown above (Par. 13). In the case of the sugar solu- the osmotic pressure exerted by the dissolved sugar molecules is nerically equal to the gas pressure which the same molecules would rt if the same weight of sugar existed in gaseous form in the same volume l at the same temperature. This is the foundation of **Van't Hoff's ory of solutions.** Instead of measuring the osmotic pressure directly, s possible to calculate it from the changes of the vapor pressure or of freezing point, due to the addition of the solute to the solvent.

15. **Electrolytes form an exception.** However, the above law does hold good in general and all aqueous solutions which are electrolytes form important exception, if we base the calculation on ordinary molecular ights in the same way as in the above case of sugar. This discrepancy removed by the hypothesis of an electrolytic dissociation in solutions anck and Arrhenius). According to Arrhenius not all the molecules the dissolved substance are electrolytically active, but only those which "dissociated" into electrically charged ions; this is the foundation of **electrolytic dissociation theory.** In applying the laws of the osmotic sure to electrolytes a larger number of molecules must therefore be umed according to the degree of dissociation.

LATION BETWEEN MASS AND ELECTRIC QUANTITY IN ELECTROLYTIC REACTIONS

16. **Faraday's first law** gives the exact relation between the weight of products of electrolysis and the quantity of electricity passing during electrolysis. There are always two reactions. One is the anodic reac- n, its product or products appearing at the anode. The other is the hodic reaction, its product or products appearing at the cathode. raday's first law states that if nothing but the one desired reaction occurs the anode or cathode as the result of the passage of the electricity, the antities of material changed at the anode or cathode depend only on the antity of electricity which passes, measured in coulombs or ampere- onds; in other words, these quantities depend only on the product of the rent in amperes and the time. With i amperes the same quantities of micals are changed in t seconds, as with i/n amperes in nt seconds, where nay be anything; the quantities depend only on the product of current l time and not on anything else, for instance, not on the voltage or on size of the electrodes or on the temperature, etc. This should not be understood; all these statements are valid under the supposition placed the beginning of our statement of Faraday's first law, namely that noth- but the one desired reaction takes place. As long as this is true, the quan- es of materials changed are strictly proportional to the quantity of elec- city passing. But if, for instance, by raising the voltage, a new reaction started, the conditions are of course changed.

17. **Faraday's second law** gives the numerical relation between the antity of electricity and the quantity of material changed. It can be st easily expressed for the special case that the chemical reactions oc- ring at the anode and cathode are simply a liberation of a gas or a deposi- n of a metal. For this case Faraday's second law states that the quantity gas set free or of metal deposited is proportional to the **equivalent ight** of the gas or metal, and that 96,540 coulombs deposit or set free **gram-equivalent** of metal or gas. The equivalent weight, or gram- ivalent is defined as the atomic weight divided by the valency. For tance, 63.6 is the atomic weight of copper; the equivalent weight is 63.6/2 6.8 for a bivalent salt, like copper sulphate, and 63.6 for a monovalent t like cuprous chloride. Hence 96,540 coulombs deposit 26.8 g. of per from copper sulphate, but 63.6 g. from cuprous chloride.

18. **Faraday's law stated in general form.** Faraday's law will now stated in what appears to the writer to be the most general and complete m. It is valid for all electrolytic processes and all such processes require entially direct current.

n any electrolytic process there is chemical reduction at the cathode and emical oxidation or adduction at the anode. Reduction means a loss of nds, adduction a gain of bonds. Exactly as many bonds are lost at the

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cathode as are gained at the anode. *If the number of bonds lost at the cathode and gained at the anode in an electrolytic process is n, then each symbol of the elements in the equation of the reaction represents a gram-atom of the element involved in the reaction, when* $96{,}540 \times n$ *coulombs are passing.*

19. The figure 96,540 coulombs per monovalent gram-ion is based on the atomic weight of silver 107.93 and the electrochemical equivalent of silver adopted by the International Electrical Congress of Chicago in 1893 in the definition of 1 amp., namely 0.001118 g. of silver per coulomb. This gives $107.93 \div 0.001118 = 96{,}538.5$ coulombs for the monovalent gram-ion of silver, or approximately 96,540, which figure is very widely used.

20. Definitions of valence and bonds. For the understanding of Faraday's law which is the most fundamental law of electrolysis, a proper understanding of the terms valence and bonds is absolutely essential. This subject must be approached from the chemical side and for the purpose of acquainting electrical engineers with these fundamental chemical conceptions, the notation of Prof. Otis C. Johnson seems to be particularly suitable. While for a detailed study of notation the reader must be referred to Prescott and Johnson's "Qualitative Chemical Analysis," the following summary will be sufficient to explain the chief points.

The **valence** represents the number of bonds uniting an element with others in a chemical compound. A **bond**—that is, a unit of **active valence**—is either a positive one or a negative one. The addduction of an element is shown by an increase, and its reduction by a decrease of the number of bonds. Hydrogen (in combination) has always one positive bond. Oxygen (in combination) has always two negative bonds. Free elements have no bonds. The sum of all bonds of any compound is zero. In salts the bonds of the metal is always positive. In acids and in salts the acid radical has always negative bonds.

21. Determination of valence. These rules enable one easily to determine the valence in any compound. For instance, in HCl, H has one positive bond, hence Cl must have one negative bond in order to have the sum of all the bonds in the molecule equal to zero. In all chlorides Cl has one negative bond. In H_2SO_4 we see that H_2 has two positive bonds and O_4 eight negative bonds, hence S has six positive bonds, or the radical SO_4 has two negative bonds. In CuCl, Cl has one negative bond, hence Cu one positive bond. In $CuSO_4$, SO_4 has two negative bonds, hence Cu two positive bonds. In other words, Cu is monovalent in the chloride and bivalent in the sulphate. CO_3 in carbonates has two negative bonds. ClO_3 in chlorates has one negative bond. See also Par. **142** and **143**.

22. Example. The final step of the **Siemens and Halske copper process** consists in depositing copper on the cathode from a $CuSO_4$ solution and simultaneously oxidizing ferrous sulphate to ferric sulphate at a carbon anode in a diaphragm cell. The equation in its simplest form is

$$\underset{159.66}{CuSO_4} + 2\underset{303.92}{FeSO_4} = \underset{63.6}{Cu} + \underset{399.98}{Fe_2(SO_4)_3}$$

The figures given below the chemical symbols are the molecular weights. Cu has two positive bonds in $CuSO_4$ and when deposited as metal at the cathode it has no bonds; hence the loss of bonds of Cu in its reduction to the metallic state is two. Fe in $2FeSO_4$ has two positive bonds, hence the 2Fe have four positive bonds; but Fe has three positive bonds in $Fe_2(SO_4)_3$ and Fe_2 six positive bonds; hence in the oxidation from ferrous to ferric sulphate two positive bonds are gained. Therefore, if the symbols in the above equation represent gram-atoms or gram-molecules, the reaction corresponds to the passing of $2 \times 96{,}540$ coulombs through the cell. The $2 \times 96{,}540$ coulombs deposit in this process 63.6 g. of copper, or 100.00 coulombs 33 g. of copper. The above equation may be completely interpreted as follows: If $2 \times 96{,}540 = 193{,}080$ coulombs pass through the cell, 159.66 g. of $CuSO_4$ and 303 92 g. of $FeSO_4$ are changed into 63.6 g. of Cu and 399.98 g. of $Fe_2(SO_4)_3$. This example makes it clear that the statement of Faraday's second law in Par. **17** for the special case of metal deposition follows directly from the more general statement of the law in Par. **18**.

The Siemens and Halske process of producing copper has never attained industrial importance. But it has been chosen here as an example for the explanation of Faraday's law, since the importance of valence is clear

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lustrated by a comparison of this process with that of Hoepfner which as devised later to compete with the Siemens and Halske process. While ılphate solutions are used in the latter, Hoepfner proposed to use a chloride ılution. The ferric sulphate and cupric chloride are used for leaching ıe ore.

23. Example. The scheme of the **Hoepfner copper process** was ıssentially to deposit copper on copper cathodes from a cuprous chloride ılution and oxidize simultaneously the cuprous chloride to cupric chloride ı carbon anodes, the essential reaction being

$$2CuCl = CuCl_2 + Cu \ . \qquad (7)$$
$$198.1 \quad 134.5 \quad 63.6$$

The figures placed below the chemical symbols represent again the ‹eights, found from the table of atomic weights. In this case Cu in the ıprous chloride CuCl, has one positive bond, while it has two positive bonds ı cupric chloride $CuCl_2$. At the cathode the reduction of one CuCl to ıetallic Cu (which has no bonds) involves therefore a loss of one positive ond. At the anode the adduction of one CuCl to $CuCl_2$ involves the gain of ne bond. Hence in this case, we have a monovalent reaction, the change f bonds being 1, and we find that when 96,540 coulombs pass through the ell, 198.10 grams of CuCl are changed into 134.5 grams $CuCl_2$ and 63.6 rams Cu. The metallic copper is the principal product in the process, 6,540 coulombs deposit 63.6 grams of copper or 100,000 coulombs deposit 5 grams of copper, *i.e.*, just twice the amount obtained with the same urrent and in the same time by the Siemens and Halske process.

24. Explanation of different outputs in the two examples. (Par. 2 and 23.) It is quite clear from the above argument what causes the dif-ɛrent output of both processes; it is simply the fact that Cu has two bonds or ı bivalent in $CuSO_4$ and has one bond or is monovalent in CuCl. It is lso clear that to find the amount of an element set free from a compound is not necessary to write down the whole equation of the reaction, as was one above for the sake of completeness. We can state that if 1 gram-tom of a metal is deposited in free metallic state by electrolysis, 96,540 oulombs are necessary for deposition from a monovalent compound (like ‹uCl), twice as many from a bivalent compound (like Cu_2SO_4), three times ı many from a trivalent compound, etc. But this rule is only a special case nd does not give any information, for instance, on the quantity of ferrous ılphate oxidized to ferric sulphate in the Siemens and Halske process.

25. Procedure in calculations. The method of writing down the ‹hole **equation,** determining the number of bonds lost and gained and apply-ıg the above rule gives complete information in all cases on the relation be-ɛween the quantity of electricity, which passes a cell and all the quantities hanged thereby in chemical composition.

26. Method of calculation under the electrolytic dissociation heory. The above method of calculation becomes easier if we use the pic-ure of the electrolytic dissociation theory. The equation of the Siemens nd Halske process is then written in the form

$$Cu^{\cdot\cdot} + SO_4'' + 2Fe^{\cdot\cdot\cdot} + 2SO_4'' = Cu + 2Fe^{\cdot\cdot\cdot} + 3SO_4'', \qquad (8)$$

hat is, instead of $CuSO_4$ in solution we write $Cu^{\cdot\cdot} + SO_4''$, the copper sul-hate being dissociated into its ions, the positive copper ion $Cu^{\cdot\cdot}$ and the egative ion SO_4''. Each dot at the top of $Cu^{\cdot\cdot}$ represents a positive electric harge. Each stroke at the top of SO_4'' represents a negative electric charge. ach such charge, positive or negative, is 96,540 coulombs, if the chemical ymbols represent gram-atoms or as we now say, gram-ions. The gram-ion ‹u$^{\cdot\cdot}$ is bivalent and charged with $2 \times 96{,}540$ coulombs. Each gram-ion ‹e$^{\cdot\cdot}$ (ferrous) is bivalent and charged with $2 \times 96{,}540$ coulombs. The ram-atom Cu (metal deposited on the cathode) is not charged. Each ram-ion Fe$^{\cdot\cdot\cdot}$ (ferric) is trivalent and charged with $3 \times 96{,}540$ coulombs. he above ionic equation may be somewhat simplified by writing

$$Cu^{\cdot\cdot} + 2Fe^{\cdot\cdot\cdot} = Cu + 2Fe^{\cdot\cdot} \qquad (9)$$

If this equation shall be right, not only the chemical symbols but the lots must balance on both sides, since otherwise free electrostatic charges ould appear somewhere. In this case we see $Cu^{\cdot\cdot}$ has 2 charges and each of he two $Fe^{\cdot\cdot}$ has also 2 charges, hence the total sum is 6 charges on the left ide of the equation. On the right side Cu has no charge, each of the two ‹e$^{\cdot\cdot\cdot}$ has 3 charges, hence the total sum is again 6 charges.

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What happens according to this view is that at the cathode a bivalent $Cu^{\cdot\cdot}$ ion (from copper sulphate) is reduced to metallic copper, thus giving off 2 charges to the cathode, while simultaneously two $Fe^{\cdot\cdot}$ ions (ferrous) are oxidised to two $Fe^{\cdot\cdot\cdot}$ ions (ferric) at the anode, each taking one charge from the anode. Hence the above ionic reaction will take place in the electrolyte when $2\times96{,}540$ coulombs pass through it, entering from the anode and leaving into the cathode.

27. Reconcilement of theories. While these statements differ greatly from our former discussion of the same equation in the notation adopted and in the expressions employed it will be seen that there is no essential difference. The two dots on top of $Cu^{\cdot\cdot}$, *i.e.*, the two positive charges, represent exactly the same thing as the two positive bonds which Cu has in Johnson's notation. According to the electrolytic dissociation theory the reactions in electrolysis are reactions between ions. The characteristic feature of an ion is, that it is electrically charged. Any gram-ion—whatever may be its chemical nature—carries one or two or three, etc., charges, each of 96,540 positive or negative coulombs, according to whether it is monovalent or bivalent or trivalent and whether it is positive or negative. There are everywhere in the interior of the electrolyte as many positive as there are negative ions, *i.e.*, there is no free electricity anywhere.

28. Difference between electrolytic and chemical dissociation. It should be emphasized that electrolytic dissociation is essentially different from chemical dissociation. The ion $Cu^{\cdot\cdot}$ is essentially different (in electric charge, energy content, properties) from the atom Cu or from the monovalent ion $Cu^{\cdot}$.

29. Examples. To write the equation of the Hoepfner process in the notation of the electrolytic dissociation theory, we write $Cu^{\cdot}+Cl'$ instead of CuCl (in solution) and $Cu^{\cdot\cdot}+2Cl'$ instead of $CuCl_2$ (in solution). Hence the equation becomes

$$2Cu^{\cdot}+2Cl'=Cu^{\cdot\cdot}+Cl'+Cu \qquad (10)$$

or

$$2Cu^{\cdot}=Cu^{\cdot\cdot}+Cu. \qquad (11)$$

At the anode one monovalent $Cu^{\cdot}$ ion (cuprous) is oxidised to $Cu^{\cdot\cdot}$ (cupric), taking one charge from the anode. Simultaneously one monovalent $Cu^{\cdot}$ ion (cuprous) is reduced to metallic copper Cu at the cathode-giving off one charge to the cathode.

30. Application of electron theory. We may go a step further and apply the modern theory of electrons to our problem. This has been done by Nernst. We will assume there are positive and negative electrons, although only negative electrons have so far been isolated. We may consider them as kinds of new elements (only for the sake of illustration), with so small atomic weights that, for all practical calculations, they may be considered zero; while their characteristic and distinguishing feature is that each positive electron has an electric charge of 96,540 positive coulombs and each negative electron has an electric charge of 96,540 negative coulombs. Nernst, therefore, considers any monovalent positive gram-ion as a compound of the gram-atom with a positive electron; also any bivalent gram-ion as a compound of the gram-atom with two electrons, and so on. This view emphasises the essential difference between atoms and ions, and at the same time gives a very convenient scheme for applying Faraday's law, which appears as a consequence of the laws of definite and multiple proportions. Johnson's bonds are, then, a very substantial thing. His positive bonds are positive electrons, and his negative bonds are negative electrons. This view, although it may be called very hypothetical, offers the safest method of applying Faraday's law. There is no possibility of making a mistake if we always keep the mechanical model in mind.

31. Definition of a "Faraday."—The charge of a monovalent positive ion, which is 96,540 coulombs per gram-equivalent is the fundamental unit for all electrolytic processes and is called one **Faraday** and designated by F, so that F represents one positive electron and $-F$ one negative electron. A bivalent ion is charged with 2F, etc.

32. Use of the Faraday notation. With this notation it is easy to write down the anodic and cathodic reactions separately. For instance, in case of the Siemens and Halske process the anodic reaction is $2F+2Fe^{\cdot\cdot}=2Fe^{\cdot\cdot\cdot}$, two positive electrons being absorbed by the two $Fe^{\cdot\cdot}$ ions from the anode.

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ile the cathodic reaction is $Cu^{\cdot\cdot} = Cu + 2F$, one Cu ion giving off its two itive electrons to the cathode.

33. Use of larger units in practical work. In the above we have based calculation on 96,540 coulombs as the charge of 1 gram-ion. This is laboratory unit, but although universally used in discussions of Faraday's , it seems too small for practical purposes. If one monovalent gram-ion ries 96,540 coulombs, then one monovalent kilogram-ion carries a charge 96,540,000 coulombs or 26,817 amp-hr. Hence, if the symbols in the ıation of the reaction represent kilogram-atoms, then the reaction re- ires 26,817 amp-hr. if monovalent, $2 \times 26{,}817$ amp-hr., if bivalent, etc.

34. Practical use of the gram-equivalent. Finally the above nu- rical relations may be very briefly stated by using the term **gram-equiva-** **ıt** which means gram-ion divided by the valency, so that one gram-equiva- it equals a gram-ion if it is monovalent, but one-half gram-ion if it is valent as already explained in Par. **24**. In the same way the term kilo- ım-equivalent means kilogram-ion divided by valency. Then Faraday's w states that 1 gram-equivalent of any chemical composition whatever rries an electric charge of 96,540 coulombs. One kilogram-equivalent rries an electric charge of 26,817 amp-hr.

35. Johnson's rule for balancing equations. In the procedure recom- ended above for the application of Faraday's law a difficulty may be found writing down the equation of the reaction. Since in any electrolytic ocess we have to do with reduction and adduction the following rule of of. O. T. Johnson for **balancing equations** of this kind may be found eful. This rule states that "the number of bonds changed in one molecule each shows the number of molecules of the other which must be taken," e words "each" and "other" referring to the adducing and reducing ents. One example may illustrate this rule, which appears to be purely rmal from a chemical point of view, while its electrical meaning will be own below. In the Bunsen cell Zn is oxidized; it becomes $ZnSO_4$. The etal Zn has no bond. Zn in $ZnSO_4$ has two bonds, hence the increase in nds is two. There are several actions possible at the other electrode. We ay consider that NO is developed. N in HNO_3 has five positive bonds, hile in NO it has two positive bonds, hence the decrease in bonds is three. ow Johnson's rule states that we have to take three molecules of Zn and o molecules of HNO_3 and we get the equation

$$3Zn + 3H_2SO_4 + 2HNO_3 = 3ZnSO_4 + 2NO + 4H_2O. \qquad (12)$$

36. Application of Johnson's rule. This rule becomes self-evident if pplied to an electrochemical action. It simply means that just as much ectricity passes from the anode into the electrolyte as from the electrolyte to the cathode. In the case of the Bunsen cell if the chemical symbols present gram-atoms, then, as Zn gains two bonds and as we have three atoms, $3 \times 2 \times 96{,}540$ coulombs pass into the electrolyte from the anode. n the other hand, N loses three bonds, and, as two N are reduced, $2 \times 3 \times$,540 coulombs are given off to the cathode. Of course we may also con- der HNO_3 to be ionized into H and NO_3 ions, both monovalent, etc. The sult is the same. Johnson's rule for balancing equations enables one to rite down the equation which represents the electrochemical action, and in e further calculation there is no mistake possible if one keeps in mind that ch bond corresponds to 96,540 coulombs, providing the chemical symbols present gram-atoms.

37. Faraday's law is always exactly fulfilled in the sense that the anodic dduction and cathodic reduction of given quantities of materials require certain amount of coulombs, not more nor less. For instance, the deposi- on of 1 gram-atom or 63.6 g. of copper from the solution of a monova- nt cuprous salt requires 96,540 coulombs. But this does not mean that if e send 96,540 coulombs through such solution, we must always deposit 3.6 g. of copper on the cathode. It may be that we have a second action at the cathode besides copper deposition, for instance, evolution of ydrogen gas. The conditions may be such that, say 75 per cent. of the oulombs only deposit copper; then we get $0.75 \times 63.6 = 47.7$ g. of cop- er. The other 25 per cent. of the coulombs deposit hydrogen and there- re evolve 0.25 gram-atom = 0.25 g. hydrogen. Thus Faraday's law fulfilled, but in practice we are interested in this case only in the copper

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deposition; we consider the hydrogen evolution as waste and say that we have deposited the copper with an "ampere-hour efficiency" of 75 per cent. The ampere-hour efficiency therefore indicates to which degree the one reaction which we desire to obtain (in the above example, the copper deposition) really takes place. It is also called "current efficiency" although somewhat loosely.

HEAT AND CHEMICAL ENERGY

38. Transformations of energy. The symbols in a chemical equation, besides being considered as masses and volumes, and as masses charged with electricity, may also be considered as masses endowed with energy, because simultaneously with the transformation of matter there is a transformation of energy. Since the energy stored in the starting materials differs from the energy stored in the final product of a process, the balanced equation of the chemical transformation of matter no longer balances as an equation for energy transformation. For instance, if carbon burns to carbon dioxide, the ordinary chemical equation is

$$C + O_2 = CO_2. \qquad (13)$$

But we know that this reaction evolves heat; *i.e.*, if at the end of the reaction the CO_2 is brought back to the same temperature as that of C and O_2 at the start, a certain amount of heat is carried off to the surroundings, and from experiments this heat is found to be 97,200 g-cal., if the symbols in the above equation represent gram-atoms. To balance the energy equation we must therefore write

$$C + O_2 = CO_2 + 97{,}200 \qquad (14)$$

This equation states that the combination of 12 g. C with 32 g. O, forming 44 g. CO_2, evolves 97,200 g-cal.

39. A thermochemical equation is therefore the total sum of the heat balance sheet of a process. To give this for any reaction, we need thermochemical data, namely the formation heats of all compounds.

40. Thermochemical data. For these, as they have been determined, the reader must be referred to the large thermochemical treatises of Berthelot, Thomsen and others. A very convenient and handy set of those data which are most important for the engineer, may be found in J. W. Richards' "Metallurgical Calculations," Vol. I.

41. Use of different units. In applying these data, attention must be paid to the fact that different authors write the same equation in different ways. Thus, the above statement of the formation heat of carbon dioxide is written by Richards, Hess and Naumann in the form $(C,O_2) = 97{,}200$; by Berthelot in the form $(C,O_2) = 97.2$; by Ostwald in the form $(C,O_2) = 972K$: *i.e.*, if the chemical symbols of the reacting substances represent gram-atoms, then Richards, Hess and Naumann give the energy in gram-calories, Berthelot in kilogram-calories and Ostwald in terms of a unit 100 times as large as a gram-calorie.

Sometimes the energy is given in British thermal units; this unit is the heat that will raise the temperature of 1 lb. of water 1 deg. fahr. Thus since 1 deg. cent. = 1.8 deg. fahr., we have simply to multiply the figures in the Richards-Hess-Naumann notation by 1.8 and the thermochemical equation will be correct if the chemical symbols represent pound-atoms. Thus $(C,O_2) = 97{,}200 \times 1.8 = 174{,}960$ B.t.u. states that the combination of 12 lb. C with 32 lb. O_2, forming 44 lb. CO_2 evolves 174,960 B.t.u.

42. Application of heat balance sheet. In many electric furnace processes the object is to heat the charge up to a certain high temperature, at which the desired chemical reaction will then go on. Whether the reaction will evolve or consume energy will be seen from the thermochemical heat balance sheet. If it evolves energy, then this amount is added to the heat produced by the electric current. If it consumes energy, then this amount must be furnished by the electric current. To find the electrical energy equivalent to the heat given in calories, it is to be noted that 1 cal. = 4.186 watt-sec. Direct currents and alternating currents are equally suitable for producing the heat effect.

43. Change of reaction heats with temperature. In making up a heat balance sheet, the thermochemical data relating to the temperature at which the reaction is carried out, must be chosen since the reaction energy depends on the temperature. The data may not be available for the desired

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emperature. In such cases the following consideration is often useful, if he specific heats of all substances which are represented in the equation are nown. Suppose a certain reaction evolves a calories at the temperature, t_1, and we want to find the reaction heat at the higher temperature, t_2. Then ve consider the materials on the left hand of the equation, *i.e.*, the starting naterials, and raise them from t_1 to t_2; the heat, necessary for this purpose, nay be b calories and is directly found from the specific heats of the starting naterials and the temperature difference, t_2-t_1. That is b more calories are now stored in the system than were in it at the temperature, t_1. We iow let the desired chemical reaction go on at the temperature, t_2. This may revolve, x, calories, which is the figure to be determined. If we finally cool he system back to the temperature, t_1, it gives out a certain amount of heat, , which can be found for the temperature difference, t_2-t_1, and the specific eats of the end products. Then we know that the system has stored in it $b-x-c$) more calories than at the start, which according to the principle of the conservation of energy must be equal to $-a$, or $x=a+b-c$.

CHEMICAL AND MECHANICAL ENERGY

44. Definition of liter-atmosphere. If as a result of a reaction between solid or liquid bodies a gas is evolved, work is done against the pressure of the atmosphere. The work done by the evolution of 1 liter of gas under atmospheric pressure is 1 liter-atmosphere.

1 liter-atmosphere = 10.333 kg-m.
= 24.2 g-cal.
= 101.3 watt-sec. (15)
= 0.136 horsepower-second.

45. Work performed by evolution of gas. For instance, if hydrogen and oxygen gas are produced under atmospheric pressure by electrolysis of a dilute acid or alkaline solution, 18 kg. water yield 2 kg. H, occupying 22,420 liters at 0° C, and the work done in expanding the hydrogen gas against the pressure of the atmosphere is 22,420 liter-atmospheres = 543 kg-cal. = 2,271 kw-sec. Simultaneously 16 kg. O, occupying 11,210 liters, are evolved and the work done in expanding the oxygen gas against the pressure of the atmosphere is 11,210 liter-atmospheres = 271 kg-cal. = 1,135 kw-sec. Hence the total work done in expanding both gases to 33,630 liters is 814 kg-cal. = 3,406 kw-sec. This energy consumed is, of course, not to be confounded with the energy required for the electrolytic decomposition of the water. It is simply the mechanical work performed in expanding the gases against the pressure of the atmosphere.

A very simple way to calculate this work approximately is to remember the formula $p\,v = RT$, in which R very approximately = 2, if $p\,v$ is given in gram-calories and the mass of 1 gram-molecule is considered. In words, the work done in expanding 1 gram-molecule of any gas from a solid or liquid to gas at the absolute temperature T is 2T g-cal.; for instance, at 0 deg. cent. or 273 deg. absolute temperature it is 546 g-cal. (as compared with 543 found above). In the reverse change from gas to solid the same amount of work is performed upon the system or the same amount of energy is gained by the system.

46. Expansion of gas at constant pressure. The characteristic feature of processes like those just described is that they take place at constant pressure. In general if a gas expands at constant pressure, p, from volume, v_1 to v_2, the work done is $p\ (v_2-v_1)$. In the special case that a gas expands from a solid or liquid, the volume of the solid or liquid, which disappears is negligible compared with the gas formed and $v_1 = o$, from which results at once the above calculation.

47. Expansion of gas at constant temperature. An entirely different case is the calculation of the work done when a given mass of gas expands its volume at constant temperature, the pressure decreasing correspondingly. For 1 gram-molecule, expanding from volume v_1 to volume v_2 at constant temperature, T, this work is

$$R\,T\,\log_e \frac{v_2}{v_1}, \qquad (16)$$

where $\log_e$ means the natural logarithm. In view of the parallelism between gaseous pressure and osmotic pressure in solutions, the above statements on gases may be made in an analogous way for solutions.

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CHEMICAL AND ELECTRICAL ENERGY

48. Transformation of electrical energy to chemical energy. In electric-furnace reactions, as noticed above in Par. **42**, electrical energy is changed into chemical energy, but this transformation is only partly direct, since that part of the electrical energy which serves for raising the charge of the furnace to the desired temperature (physical change) is first changed into heat. Another amount of electrical energy may be necessary for the chemical reaction according to the thermochemical balance sheet. Such an electric-furnace process should therefore be treated exactly like a thermochemical process (**38 to 43**). Direct current and alternating current are equally suitable.

49. A direct change of electrical energy into chemical energy occurs in electrolytic processes requiring direct current, and we will first assume that no other forms of energy besides electrical and chemical are involved in the reaction. This assumption is never strictly fulfilled, but approximately in many cases. Under this supposition the chemical equation of any electrolytic reaction gives directly the e.m.f. required to perform it or the e.m.f. which it can give out according to whether we have to do with an electrolytic process changing electric energy into chemical energy or with a battery changing chemical energy into electrical energy.

50. Calculation of e.m.f. of reaction. We need for this calculation the thermochemical data to write down the energy-balance sheet; while we thereby get the energy of the reaction in heat units or calories, we can easily change it into electrical units or watt-seconds = volt-ampere-seconds. From Faraday's law we know the coulombs or ampere-seconds which correspond to the same equation. By dividing the volt-ampere-seconds by the ampere-seconds, we get the volts corresponding to the reaction.

51. Example. In the **Daniell cell** the essential reaction is

$$Zn + CuSO_4 = Cu + ZnSO_4. \qquad (17)$$

According to Richards, "Metallurgical Calculations," Vol. I, p. 24, the formation heats of $ZnSO_4$ and $CuSO_4$ from the elements, if the chemical symbols represent gram-atoms, have the following values in gram-calories:

$$Zn + S + O_4 = ZnSO_4 + 248{,}000 \text{ (in solution)},$$
$$Cu + S + O_4 = CuSO_4 + 197{,}500 \text{ (in solution)}.$$

By subtraction we get the energy balance of the Daniell cell

$$Zn + CuSO_4 = Cu + ZnSO_4 + 50{,}500. \qquad (18)$$

Since the change of bonds or change of valency is two, we know that $2 \times 96{,}540$ coulombs are involved in the reaction which gives out 50,500 g-cal. or $50{,}500 \times 4.186 = 211{,}400$ watt-sec. or volt-ampere-seconds. This divided by $2 \times 965{,}400$ amp-sec. gives 1.1 volt which is almost exactly correct.

52. As a second example we may use our former equation of the Siemens and Halske copper process. From Richards (Vol. I, pp. 24 and 25) we find

$$Cu + S + 4O = CuSO_4 + 197{,}500,$$
$$2Fe + 2S + 8O = 2FeSO_4 + 469{,}800,$$
$$2Fe + 3S + 12O = Fe_2(SO_4)_3 + 650{,}500.$$

By subtracting the sum of the first two equations from the third equation we get

$$CuSO_4 + 2FeSO_4 = Cu + Fe_2(SO_4)_3 - 16{,}800. \qquad (19)$$

Hence in order to let this reaction go on from the left to the right hand in the equation, if each symbol of an element means a gram-atom, energy in the amount of 16,800 g-cal. must be furnished, which is equal to about 70,000 volt-amp-sec. Since this reaction involves the passage of $2 \times 96{,}540$ amp-sec., the theoretical voltage which must be applied is somewhat less than 0.4 volt.

53. Thomson's rule. Let W be the total energy of the reaction in gram-calories when all symbols of the elements in the equation of the reaction represent gram-atoms. The same energy, measured in watt-seconds, is 4.186 W. The electrical work equals electromotive force × coulombs = $e \times n \times 96{,}540$, if e is the electromotive force in volts and n the change of valence (change of bonds) in the reaction. If the total chemical energy equals the electrical energy, we get

$$e = \frac{4.186\ W}{96{,}540\ n} = 0.0000434\ \frac{W}{n}. \qquad (20)$$

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At ordinary temperatures this rule is, in general, approximately fulfilled nd is therefore exceedingly useful for making a first approximate calculation.

54. Terminal voltage. The voltage, e, is the e.m.f. absorbed or produced in the electrochemical process. It is different from the voltage at the erminals. The voltage at the terminals of a battery equals the e.m.f., minus the voltage drop due to internal resistance. The voltage at the erminals of an electrolytic cell through which electricity is passed from an utside source, equals the e.m.f., e, of the reaction plus the voltage drop due to nternal resistance.

CHEMICAL ENERGY, ELECTRICAL ENERGY AND HEAT

55. Error in Thomson's rule. Thomson's rule is wrong in principle ecause in an electrochemical action we never have an interchange of chemical energy and electrical energy alone, since heat is always involved. This oes not mean the Joulean heat which, of course, is also present. We may ssume we have an electrolytic system of such dimensions and design that ts internal resistance is so small that the Joulean heat developed in it is negligible compared with the amount of energy involved in the reaction. Under uch conditions we know from experience that the cell while electricity passes hrough it, either tends to cool or to heat. To maintain the temperature onstant it is therefore necessary to supply heat from the surroundings or to arry it off to the surroundings. In the case of a battery, if it tends to cool, nd we supply heat to maintain the temperature, not only chemical energy ut also the heat supplied during discharge are changed into electrical energy; ence the e.m.f. at that temperature has a greater value than that found rom Thomson's rule. If the battery tends to give up heat during the passage f the electricity, heat is given off to the surroundings, and the e.m.f. s smaller than found by Thomson's rule.

56. Distinction between energy of reaction and capacity for performing work. This question is intimately connected with the essential ifference between the total energy of a reaction at a certain temperature, as defined in Par. **38** to **43** and its capacity of performing work. The reason is hat among all different forms of energy, heat has an exceptional place. We an always change all other kinds of energy completely into heat, but we annot do the reverse. In case of a chemical reaction we can change the hemical energy completely into heat and this is exactly what we are doing in hermochemistry when we determine the heat or **energy of a reaction.**

57. The capacity of performing work (mechanical work in the expanion of gases or electric work in case of a battery) is something different. As an example, let us assume a concentration cell, consisting of two different oncentrations of the same salt solution, each containing an electrode made of he metal of the salt. If then the reaction is that at the anode metal is issolved and forms more salt, while simultaneously salt disappears at the athode, metal being deposited, then the energy corresponding to the soluion of metal from the anode and deposition of exactly the same amount of netal on the cathode is zero. If we assume further that we have to do with olutions so diluted that the energy of further diluting them is zero, then the nergy corresponding to the concentration changes in the cell is also zero. Hence the total chemical energy of the reaction in the cell is zero. Nevertheless the cell will give out electricity and will perform work, the electricity roduced being in such a direction as to equalize the concentrations (*i.e.*, he electricity passes in the cell from the dilute to the concentrated solution, ecause under this condition more salt is formed in the dilute solution from he anode, while the concentrated cathode solution is diluted by metal being eposited on the cathode). Of course, the energy must come from some ource, and under the conditions of the experiment it must come from heat; .e., the cell while giving out electricity tends to cool down, and heat must be upplied from the outside to keep the temperature constant. This is therefore a case in which the chemical energy of reaction is zero, but its capacity f performing work has a positive value; correspondingly the e.m.f. would e zero according to Thomson's rule, but has in reality a positive value.

58. Helmholtz equation of energy. If W = energy of the chemical eaction at a certain absolute temperature T and if W_0 is the maximum mount of work which it is capable of performing at that temperature under

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ideal conditions (characterized by complete "reversibility"), then Helmholtz has shown that

$$W_0 = W + T\frac{dW_0}{dT}. \quad (21)$$

Helmholtz calls W the total energy of the reaction and W_0 the **free energy**, i.e., that amount which is free to perform work. The second term at the right hand is the temperature coefficient of the free energy multiplied by the absolute temperature.

59. Gibbs-Helmholtz equation. In the case of an electrolytic reaction which is supposed to be reversible, W_0 is the total energy of the reaction in gram-calories when all chemical symbols of the elements in the equation of the reaction represent gram-atoms. Measured in watt-seconds, this energy is 41.86 W. The free energy W_0 is in this case the electrical work $= e \times n \times 96{,}540$ watt-sec. if e is the electromotive force and n the change of valence in the reaction. The above energy equation may therefore be transformed into

$$e = 0.0000434\ \frac{W}{n} + T\frac{de}{dT}, \quad (22)$$

where e is given in volts, W in gram-calories and T is the absolute temperature. This equation differs from Thomson's rule by the second term on the right hand which may be considered as a term of correction or refinement, since for approximate calculations of practice, at ordinary temperature, Thomson's rule is good enough. The above equation permits the calculation of the temperature coefficient of the e.m.f., if the e.m f. and the energy of reaction are known.

ELECTRIC FURNACES

60. Distinguishing feature. There is no specific feature which distinguishes an electric-furnace reaction as a reaction from those taking place in ordinary chemical or metallurgical processes. The **distinguishing feature** rests in the apparatus, the heat required for the reaction being produced electrically. If the same amount of heat would be generated in the same material in some other way than by electricity, the reactions would be exactly the same.

61. Advantages. Compared with the production of heat in the ordinary way from fuel, electrical heat has the following advantages. First, a considerably higher temperature may be obtained; it is limited in arc furnaces by the temperature of the arc which is around 3700 deg. abs. (Waidner and Burgess) or around 3,400 deg. cent. and in resistance furnaces chiefly by structural considerations, such as the availability of insulating refractories, etc. While in ordinary chemical and metallurgical furnaces temperatures up to 2,000 deg. cent. are obtainable, temperatures up to 3,500 deg. cent. can be produced without special difficulty in the electric furnace. Secondly, for reactions requiring certain refinements, the electric furnace has the advantage of permitting easier control of the conditions of operation (temperature, chemical nature of atmosphere, etc.). On the other hand, in most places where chemical or metallurgical processes are now carried out, heat produced from electrical energy is much more expensive than heat produced from fuel.

62. Limitations. Under exceptional local conditions fuel may be so expensive and electrical energy produced, for instance, from water-power, may be so cheap, that electrical heat, because cheaper than heat from fuel, will be most economical for any purpose. Such exceptional conditions need not be considered here. Under ordinary normal conditions, the use of the electric furnace is economically restricted to reactions requiring a high temperature and to such reactions in which easy and strict maintenance of conditions of operation is of importance and in all such cases it is of the highest importance to utilize the electrical energy to the utmost. An electric horse-power-year contains the same heat as a short ton of coal with a heating value of 11,150 B.t.u. per pound.

The whole problem turns on two items: (a) The heat generated in the furnace from electrical energy and (b) the heat lost during the operation to the surroundings. If we first eliminate the size of the furnace from consideration, the rate of heat production in the furnace charge depends on the supply of electric power per unit of mass of charge, i.e., on the kilowatts per cubic meter. The rate of heat loss depends on the heat carried off by conduction

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and radiation per unit of the surface of the furnace, *i.e.*, on the kilowatts lost per square meter. Hence if the size of an electric furnace is increased, then *ceteris paribus* the generation of heat from electricity increases as the third power of the dimension, and the losses as the square of the dimension; hence the thermal efficiency of an electric furnace is the higher, the larger the size. The maximum size of a furnace is limited by the consideration that the more we increase the size, the greater becomes the difficulty of maintaining uniform conditions of operation.

ENERGY BALANCE, REFRACTORIES

63. Analysis of energy required. The energy per unit of mass is, in general, consumed in five different items, viz.:

(*a*) To produce the heat necessary to raise the starting materials to the temperature of the reaction.

(*b*) To provide the energy required for any change from solid state to liquid or from liquid to gas or from solid to gas.

(*c*) To provide the energy for the chemical reaction.

(*d*) To supply the heat lost by conduction.

(*e*) To supply the heat lost by radiation.

64. Heat necessary to raise starting materials to operating temperature. The heat necessary to raise the starting materials, if cold, to the temperature of the reaction (Par. **63a**) equals the weight of charge multiplied by temperature difference multiplied by mean specific heat.* To reduce this item of energy as much as possible, the starting materials are often preheated by waste gases, etc. It is often advantageous to divide the heating of the charge into two stages, the lower ranges of temperatures being obtained by burning fuel and only the higher range of temperatures from electrical heat.

65. Heat necessary for change of state. The heat required for a change of the charge from solid to liquid or from liquid to gas or from solid to gas (Par. **63b**) is equal to the weight of the charge multiplied by the latent heats (see J. W. Richards, "Metallurgical Calculations," Vol. I). This item of energy expense should also be eliminated wherever possible. For instance, for electric steel refining, the steel is preferably supplied to the electric furnace in molten state from the open-hearth furnace or Bessemer converter. If a gas is evolved from solid materials, the work done in the expansion of the gas must also be considered. See (**44**).

66. The energy required for the chemical reaction (Par. **63c**) at the temperature of the reaction (Par. **48** to **54**), is an item of expense, only if the reaction absorbs energy. If the reaction evolves energy, this energy is added to that of the electric current and changed into useful heat, so that the amount of electrical energy to be supplied from the outside is reduced.

67. The loss of heat by conduction (Par. **63d**) depends on the difference of temperature inside the furnace and outside and on the thermal conductivity of the furnace walls. To reduce this loss as much as possible, the furnace walls are built up of highly insulating refractory materials. In the choice of the material its heat-insulating property must be taken into consideration as well as the maximum temperature which it is intended to stand and the chemical nature of the reactions for which the furnace is to be used; further, the ability to withstand expansion and extraction must be taken into consideration. See Par. **69** to **89**.

68. The loss of heat by radiation (Par. **63e**) is treated in Par. **90**.

69. Loss of heat through terminals. All electric furnaces, except the induction furnace, have terminals (often called electrodes) for introducing the electrical energy into the furnace, and these represent the weakest point in the heat insulation. But the conduction of heat through an electrode (due to the temperature difference between its two ends) is a more complicated phenomenon than the single heat conduction through the refractory wall, because in the former case each particle of the electrode is not only a conductor of heat, but a seat of generation of new heat (from electrical energy). There is a superposition, therefore, of two phenomena; first, simple heat con-

* For tables of specific heats see J. W. Richards, "Metallurgical Calculations," Vol. I, also Sec. 4.

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duction from the hot to the cold end, and second, generation of Joulean heat within the electrode, this heat tending to flow off impartially one-half to one end and the other half to the other end. (Par. 105.)

70. Refractories. For ordinary metallurgical furnaces the refractories are generally subdivided into three classes: Acid, basic and neutral. For a basic charge no acid lining of the furnace will of course be admittable, etc. The chief constituent of acid refractories is silica and fire-clay. Lime, magnesia, bauxite* and dolomite are basic refractories. Neutral refractories are fire-clays, chromite, carbon.

71. Kieselguhr. A useful refractory for many purposes is kieselguhr† (infusorial earth). Its chemical characteristics are its siliceous nature, its easy solubility in alkalies, and its insolubility in acid or neutral solutions. It is available in the following four forms: (1) natural kieselguhr blocks (melting point 1610 deg. cent.) for insulation of moderately heated bodies and for cold-storage work; (2) pulverized kieselguhr, used as a filter for insulating purposes; (3) light weight kieselguhr insulating brick, used as an insulating backing for more refractory brick; (4) kieselguhr fire-brick for purposes where a light weight (sp. gr. 1), non-conducting, refractory brick is required (melting point 1,650 deg. cent., crushing strength 1,200 lb. per sq. in.).

72. Compounds of carbon and silicon. For the higher temperatures used in the electric furnace, certain compounds of carbon and silicon as well as pure carbon are specially suitable.‡ The various silico-carbides (siloxicon, carborundum fire-sand, etc.), or amorphous compounds of carbon and silicon, or of carbon, silicon and oxygen, are useful up to the temperature of formation of crystalline carborundum. FitzGerald recommends using a comparatively thin lining of silico-carbide to protect the walls made of fire-brick; to substitute bricks made of a silico-carbide for fire-brick, dispensing with the latter altogether, is not advisable, since the silico-carbides are much better heat-conductors than ordinary fire-bricks. F. J. Tone (*Feuary*-August, 1904) recommends carborundum fire-sand as a furnace lining. The insulating properties of the silico-carbides are greatly improved by using them in the porous state.

73. Concerning the methods of moulding silico-carbides into forms such as bricks or tiles, FitzGerald gives the following instructions: When the material is put directly into place in the furnace, where it will not have to undergo any serious mechanical strains, a mixture of the powdered silico-carbide and a solution of glue in water gives satisfactory results. In order to obtain the best results with this method the mixture should be used hot. In those cases where very high temperatures are reached this method of making bricks is to be particularly recommended, for the silica which is usually present in commercial silico-carbides is fused at high temperatures, and thus strengthens the article considerably. When there is no free silica present, and the article is made up with the glue solution, it becomes very weak and crumbles after use. It is, therefore, advisable to analyse the silico-carbide before using, and if there is no silica present a small quantity may be incorporated with the mixture. The best form of silica for this purpose is infusorial earth.

In cases where the bricks will not be exposed to such high temperatures the silico-carbide may be mixed with a dilute solution of sodium silicate. The solution used for this purpose should not, as a rule, have a greater density than 1.03 to 1.05 according to FitzGerald. Tone recommends a solution having a density of 33 deg. Beaumé (1.277), but this is for ordinary furnaces where relatively low temperatures are used.

74. Binder for silico-carbides. A very satisfactory bond for silico-carbides is found in gas tar. A good mixture contains 4 parts of the silico-carbide to 1 part of tar. In using tar, however, it must be remembered that a residue of carbon is left in the article, and this tends to diminish the insu-

*Concerning the use of alundum (made by electrically fusing and purifying bauxite) and alundum bricks as a refractory, see Saunders, *Met. & Chem. Eng'ing*, Vol. IX, p. 257, and FitzGerald, Vol, X, p. 129.

†Boeck. *Met. & Chem. Eng'ing*, Vol. XII, p. 109.

‡See for details F. A. L. FitzGerald, *Electrochem and Met. Ind.*, Vol. II (1904), p. 439.

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ing properties of the silico-carbide. Further, if the article is exposed at gh temperatures to an oxidising atmosphere the carbon residue which acts the binding agent is burnt out. If this happens the article will disinte-ate, unless the temperature and oxidising conditions are such as to cause idation of the silico-carbide and consequent binding together of the parti-s. When, therefore, the article is exposed to oxidising actions at a com-ratively low temperature, it is better to use sodium silicate as the binding ent. But where the conditions are such that neither oxidation or serious rrent leakage is to be feared, the tar bond is very satisfactory, giving ticles of considerable mechanical strength.

When an article of great mechanical strength is required, and the use of tar objectionable, the best method of making the article is, according to Fitz-rald, to cause the particles of the silico-carbide to frit together by oxidation. o accomplish this result the silico-carbide is mixed with some temporary nding agent, such as a solution of glue in water and then heated to a high mperature for several hours in a strongly oxidising atmosphere. By this eatment the grains of the silico-carbide are superficially oxidized.

75. Siloxicon. When siloxicon is heated to, or above, 2,674 deg. fahr. Acheson) or 1,468 deg. cent. in an oxidising atmosphere, decomposition takes lace. If the siloxicon be in the form of a brick or other moulded mass the action occurs on the surface, producing a vitreous glaze. In the absence of ee oxygen or in a reducing atmosphere, no such decomposition occurs, and ie temperature may be raised to the point of the formation of carborundum, pproximately 5,000 deg. fahr. (Acheson) or 2,760 deg. cent., solid crystalline rborundum remaining while the vapors of silicon and carbon monoxide are ven off. For higher temperatures carborundum is a useful refractory; it is itable up to such temperatures where it decomposes.

76. Refractories for very high temperatures. When the temperature which the refractory material is submitted may be up to or above that of ie formation of carborundum, it may be advisable, according to FitzGerald, use **cyrstalline silicon-carbide** in the first place, allowing it to be erted into **carborundum** in situ. If this is done the silico-carbide should at be analysed to determine whether oxygen compounds are present or ot. If oxygen compounds are present in appreciable quantities the silico-rbide may be unsuitable for the work, since at the temperature of the forma-on of carborundum, silica will be reduced and the refractory lining will be npregnated with metallic silicon, or the furnace will be filled with silicon apor. When the presence of the silicon is unobjectionable this reaction may e disregarded; otherwise there are two courses open; the silica may be moved or a material free from silica obtained; or from the analysis of the aterial the amount of carbon necessary to eliminate the oxygen and to form arborundum may be added to the mixture.

77. Carborundum as a refractory material. When it is desired to use arborundum directly as a refractory material the binding agents suggested in ar. **73** and **74**, for silico-carbides may be used. Carborundum may also be ade into a strong article by the oxidation or fritting method described in **4**. Another method of making articles of carborundum is by recrystalliza-ion. The carborundum in the form of grains or powder is mixed with some dhesive substance, such as a solution of glue in water, the mixture moulded the desired form and the article then placed in an electric furnace and eated to the temperature of formation of carborundum. This causes a ecrystallization of the carborundum and forms a strong article which pre-erves perfectly the form in which it was moulded. Neither the **silico-arbides** nor **carborundum** can be used as refractory materials where they ome **in contact with fused alkalies**, since these produce rapid decomposi-ion. They are also attacked by chlorine at high temperatures.

78. Binder for carborundum refractories. For using **carborun-lum** (silicon carbide) **as refractory**, E. K. Scott (*Electrochemical and Metallurgical Industry*, Vol. III, p. 140) recommends that the carborundum e ground up very fine and mixed in the proportion of three parts by weight f carborundum to one part by weight of silicate of sodium (water-glass). fter thoroughly brushing the newly set fire-brick to get rid of dust, etc. the mixture will not stick to a surface which has already been fired), the arborundum is painted on to the depth of about half a millimeter. It is hen left for 24 hr. to dry, and afterward the firing started up gradually.

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Where basic slags or basic materials have to be taken into consideration, fire clay is employed as a binder, instead of the water-glass, the proportion being usually six parts by weight of carborundum to one part by weight of fire clay. Crystolon (silicon carbide) brick may be used to advantage in the construction of electric furnace roofs of special designs (*Met. & Chem. Eng'ing*, Vol. X, p. 131). Carborundum refractories* are now available in two different types; the first containing a vitrified or ceramic binder, the second consisting entirely of carborundum. The latter type is absolutely unattacked by acids and is inert to the influence of practically all other chemical agents. It is, however, extremely expensive to produce and its use is limited to those places where the ordinary brand of carborundum refractory is not suitable. Thus for certain parts of electric furnaces, as for example, for heating furnaces of the carborundum-resistance type, it is the only material suitable for placing in contact with the carbon resistor. It also has advantages in constructing electric furnaces of the Hoskins carbon-plate type, where, owing to the resistance to oxidation of the silicon carbide coating, the life of the carbon plates is increased five to ten times. It also has remarkable value for the construction of roofs of electric steel furnaces and furnaces of a similar type.

79. The vitrified carborundum refractory has, owing to its lower cost of production, a much wider application. The special features which distinguish carborundum among refractories are high softening or decomposition point, high thermal conductivity, low coefficient of expansion, hardness and mechanical strength, resistance to acids and other chemical agents, and comparatively low density.

80. Magnesia lining. For certain purposes a pure magnesia lining is recommended by E. K. Scott who treated crude pure magnesite from Southern India by shrinking it in an electric furnace. Crystallised magnesia obtained in this way, can be used without further preparation than being crushed to suitable dimensions, as a refractory material in metallurgical practice, and an important point in connection with its use as linings for electric furnaces is that magnesia, unlike lime, does not form a carbide with carbon. Concerning the use of electrically calcined magnesia as a refractory see also FitsGerald, *Met. & Chem. Eng'ing*, Vol. X, p. 129.

81. Temperature limit with carborundum. The upper temperature limit to the use of carborundum is reached when that substance decomposes into silicon vapor and graphite. At such high temperatures the only available refractory is carbon, and the best form of carbon for this purpose is charcoal, since its electric resistivity is high. Where carbon cannot be employed, the only remedy is to dispense with a special refractory altogether and to use a solid layer of the furnace charge as lining. The solid layer is obtained from the fused charge by artificially cooling the walls of the furnace.

82. Heat insulation. Besides the ability to stand high temperatures and to resist the chemical effects of the materials in the furnace charge, the heat-insulating property is of greatest importance. It is in general necessary to make the walls of the furnace not of one single material, but to choose the inner lining with regard to the maximum temperature which it has to stand and the chemical effects to which it will be subjected from the charge, and to build the outer walls of a material of high heat-insulating quality. The total thermal resistance of a furnace wall is the sum of the resistances of the different layers of which the wall consists; these layers—the inner lining and the outer brick construction—are in series, and the thermal resistances are added in the same way as electrical resistances in series. The total thermal conductance of the furnace wall is the reciprocal of the total thermal resistance.

83. Thermal conductivities. The following table† of thermal conductivities gives the conductivities of materials suitable for heat insulation of electric furnaces, as far as determined, in the order of their heat-conducting qualities. This table is collected from J. W. Richards' "Metallurgical Calculations," Vol. I, p. 183 and from R. S. Hutton and J. R. Beard, *Elec-*

* Tone. *Met. & Chem. Eng'ing*, Vol II, p. 484.

† Other tables are given by Snyder, *Transact.* Am. Electrochem. Soc., Vol. XVIII, p. 235; Randolph, *Transact.* Am. Electrochem. Soc., Vol XX, p. 545.

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trochem. and Met. Ind., Vol. III, 1905, p. 291, and S. Wologdine and A. L Queneau, *Electrochem. and Met. Ind.*, Vol. VII, p. 383. The figures taken from Hutton are marked (H); most of the granular powders tested by Hutton and Beard just passed through a sieve with 600 meshes per sq. cm. The figures taken from Wologdine are marked (W). All the conductivities λt are given in centimeter-gram-second units, *i.e.*, each figure represents the quantity of heat in gram-calories, which is transmitted per sec. through a plate 1 cm. thick per sq. cm. of its surface when the difference of temperature between the two faces of the plate is 1 deg. cent. The thermal conductivity of various other substances is given elsewhere (see index). The figures under t represent the ranges of temperature in deg. cent. within which the conductivity figures are valid. The figures found by different investigators are considerably at variance. Probably those marked (W) are the best available at present for the grade of refractory materials on the market for everyday furnace work. Concerning the method of measuring the thermal conductivity of refractories see Clement, *Met. and Chem. Eng'ing*, Vol. VIII, p. 414.

84. Table of Thermal Conductivities of Various Substances

Substance	t	λ_t
Graphite brick (W)	100°–1000°	0.025
Carborundum brick (W)	100°–1000°	0.0231
Gas-retort carbon, solid	0°–100°	0.01477
Magnesia brick (W)	100°–1000°	0.0071
Magnesia brick	0°–1300°	0.00620
Chromite brick (W)	100°–1000°	0.0057
Masonry	—	0.0058 0.0036
Fire brick (W)	100°–1000°	0.0042
Checker brick (W)	100°–1000°	0.0039
Gas retort brick (W)	100°–1000°	0.0038
Building brick (W)	100°–1000°	0.0035
Bauxite brick (W)	100°–1000°	0.0033
Fire-brick	0°–1300°	0.00310
Fire-brick (Clement)	400°–750°	0.0021 to 0.0036
Glass pot (W)	100°–1000°	0.0027
Terra cotta (W)	100°–1000°	0.0023
Alumina brick	0°–700°	0.00204
Silica brick (W)	100°–1000°	0.0020
Kieselguhr brick (W)	100°–1000°	0.0018
Marble, white	—	0.0017
Water, uncirculated	—	0.0016 0.0012
Glass	10°–15°	0.00150
Fire-brick	0°–500°	0.00140
Plaster of Paris	—	0.0013
Water	—	0.00120
Clinker, in small grains	0°–700°	0.00110
Slate	—	0.00081
Cork	—	0.00072
Pumice	—	0.00060
Oak wood	—	0.00060
Quartz sand	18°–98°	0.00060
White Calais sand (H)	20°–100°	0.00060
Coarse carborundum (H)	20°–100°	0.00051
Fine carborundum (H)	20°–100°	0.00050
Magnesia "Mabor" brick, powder (H)	20°–100°	0.00050
Carborundum sand	18°–98°	0.00050
Rubber	—	0.00047
Pine wood	—	0.00047
Magnesia, fused, granular (H)	20°–100°	0.00047
Magnesia calcined, Grecian, granular (H)	20°–100°	0.00045
Powdered coke	0°–100°	0.00044

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84. (*Continued*)

Substance	t	λ_t
Paper	—	0.00040
Retort graphite powdered (H)	20°–100°	0.00040
Silicate enamel	20°–98°	0.00040
Coarse ordinary brick dust	0°–100°	0.00039
Fused quartz (H)	20°–100°	0.00039
Infusorial earth	0°–650°	0.00038
"Enamel" quartz (H)	20°–100°	0.00036
Magnesia calcined, "Veitsch" granular (H)	20°–100°	0.00034
Lime (H)	20°–100°	0.00029
Fire-brick, powdered (H)	20°–100°	0.00028
Chalk	0°–100°	0.00028
Powdered charcoal	0°–100°	0.00022
Cement	0°–700°	0.00017
Wood ashes	0°–100°	0.00017
Magnesia, Pattinson's light calcined, granular (H)	20°–100°	0.00016
Infusorial earth (Kieselguhr) (H)	20°–100°	0.00013
Felt	—	0.000087
Lava	—	0.00008
Cotton	—	0.000040
Wool	—	0.000035

85. Calculations of heat flow can be made analogous to calculations of electric flow. Carl Hering defines the thermal ohm* as that thermal resistance which will require a drop of temperature of 1 deg. cent. for 1 watt of heat flow. Ohm's simple law then applies numerically to calculations of thermal flows. If R is the thermal resistance in thermal ohms, W is the heat flow in watts and T the drop in temperature in centigrade degrees, then Ohm's law in thermal form is $W = T/R$, which may be unhesitatingly used in calculations, as the units are then such as will avoid all coefficients and reduction factors.

1 thermal ohm = 4.18617 gram-calorie resistance units.

1 g-cal. unit of thermal resistance = 0.238882 thermal ohm. Hering's analogous definition of the thermal mho is that conductance which will allow 1 watt of heat flow to pass when the difference of temperature is 1 deg. cent.

1 thermal mho = 0.238882 gram-calorie conductance unit

1 g-cal. unit of thermal conductance = 4.18617 thermal mhos.

86. Table of thermal resistivities and conductivities. Hering gives the following table of heat resistivities and conductivities of various refractories in his new units.

Substance	Resistivities in Thermal Ohms		Conductivities Thermal Mhos	
	in.-cube	cm.-cube	in.-cube	cm.-cube
Graphite brick	3.76	9.56	0.266	0.105
Carborundum brick	4.06	10.3	0.246	0.097
Magnesia brick	13.2	33.7	0.0755	0.0298
Chromite brick	16.5	42.0	0.0606	0.0239
Fire-brick	22.4	56.9	0.0446	0.0176
Checker brick	24.1	61.2	0.0415	0.0163
Gas retort brick	24.7	62.8	0.0404	0.0159
Building brick	26.9	68.2	0.0372	0.0147
Bauxite brick	28.5	72.4	0.0351	0.0138
Glass pot	34.8	88.6	0.0287	0.0113
Terra cotta	40.9	104.0	0.0244	0.0096
Silica brick	46.9	119.5	0.0213	0.0084
Kieselguhr brick	52.3	133.0	0.0191	0.0075

* *Met. and Chem. Engng*, Vol. IX, 1913.

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87. Example of thermal calculations. As an illustration of the simplicity of the calculations when these units are used, let the inside of a small furnace be a 6-in. cube; let the wall consist of a 4-in. layer of silica brick on the inside and 4 in. of brick on the outside. The true average cross-section of the layer of silica brick perpendicular to the heat flow (namely, the geometric mean, that is, the square root of the product of the extreme sections) for the whole furnace will be 504 sq. in. If its resistivity from the above table is 47 thermal ohms, its resistance will be

$$R = \frac{r \times l}{S} = \frac{47 \times 4}{504} = 0.37 \text{ thermal ohm.}$$

A similar calculation for the outside layer of fire-brick having a resistivity of 22 thermal ohms gives its resistance as 0.048 thermal ohm. Hence, the total is the sum of these two, which is 0.42 thermal ohm. Incidentally, it shows what a very much smaller insulating effect this much larger outside layer has.*

Suppose the drop of temperature through the wall to be 1,500 deg. cent. Then, according to the thermal ohm's law, the loss of heat will be

$$W = \frac{T}{R} = \frac{1,500}{0.42} = 3,580 \text{ watts, or about 3.6 kw.}$$

The analogy between heat flow and electric flow has been analysed very carefully by E. F. Northrup† with applications of the results to an analysis of methods for measuring thermal resistances.

88. Formulas for flow of heat through plates. The ordinary formula for the flow of heat through plates or rods of solid materials may be written:

$$W = (A/t)k\ (T - To) \tag{23}$$

Where W = the heat flow, expressed in watts, A = area of plate or cross-section of the rod, t = thickness of the plate or length of the rod, $T - To$ = the difference of temperature between the two sides of the plate or between the ends of the rod, and k = heat conductivity of the material of the plate or rod in watts per cm. cube per deg. In most practical cases of heat flow the problem is more complicated than this. Usually the heat is not flowing between parallel surfaces, or at least the areas of the two bounding surfaces are different. The above equation as it stands, applies only between parallel surfaces through a body of uniform cross-section. For bodies of other shapes Langmuir treats the case as follows. While A will vary along the path of heat flow, yet if the area of inflow and outflow is fixed, the ratio A/t will have a definite value, depending only on the shape of the body. This quantity Langmuir terms the shape factor, and represents it by S. The formula (Eq. 23) thus becomes:

$$W = Sk\ (T - To) \tag{24}$$

In case the heat conductivity is a function of the temperature, the equation should be written:

$$W = S \int_{To}^{T} k dT \tag{25}$$

S, the shape factor, is a quantity of the dimension of a length which depends only on the shape and size of the body and the position of the surfaces by which the heat enters and leaves the body.

Langmuir‡ has given formulas for the shape factor for parallel plates, concentric cylinders, concentric spheres, square edges, square corners, plane edges, plane corners, small square rods, small cubes, and for rec-

* A series of articles on heat insulations of furnace walls and the flow of heat through furnace walls has been published by Carl Hering in *Met. and Chem. Eng'ing*, Vol. IX, p. 189, 590, 652 (where there is a further table of thermal resistivities in thermal ohms); Vol. X, p. 97 and 159; Vol. XI, p. 183. On heat losses of electric furnaces see also F. A. J. FitzGerald, *Trans.* Am. Electrochem. Soc., Vol. XX, p. 281, and *Met. and Chem. Eng'ing*, Vol. X, p. 286.

† *Transact.* Am. Electrochem. Soc., Vol. XXIV, p. 85.

‡ *Transact.* Am. Electrochem. Soc., Vol. XXIV, p. 53.

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tangular parallelopipeds covered with a uniform thickness of insulation. For a cube the formula is

$$S = \frac{6\,a^2}{t} + 6.5\,a + \frac{1.2\,t}{\sqrt{1+0.16\,\frac{t^2}{a^2}}} \qquad (26)$$

where a is the length of the side of the cube and t is the thickness of the insulation covering it.

89. Abrupt discontinuities in the thermal circuit or path. It is to be considered that there is, in general, no thermal equilibrium between the furnace charge and the furnace lining, nor between the outer wall and the surrounding air. This means that at both these contact surfaces there is a sudden drop of temperature. Since this is analogous to the voltage drop at an electrode, one speaks of heat-transfer resistances at these places which are added to the heat resistance of the wall itself. These transfer resistances depend on the materials in contact as well as on the degree of motion or circulation which may exist in one of the materials. For instance, if a furnace wall is water-cooled, the transfer resistance, corresponding to the transfer of heat from the furnace wall to the circulating water (which is proportional to the difference of temperatures between wall and water, depends on the flow of water.*

90. The loss of heat by radiation from the furnace walls to the surroundings is, according to the Stefan-Boltzmann law, proportional to $T^4 - T_0^4$, where T is the absolute temperature (or deg. cent. +273) of the outer surface of the furnace wall and T_0 the absolute temperature of the surrounding atmosphere. This law is strictly correct only for absolutely "black bodies" (which is not the case for the surface of a furnace) but may be used for a first approximate estimate. The gram-calories radiated per sec. from a surface at 100 deg. cent. to the surroundings at 0 deg. vary, according to Peclet, between 0.00054 g-cal. for polished silver and 0.0164 for lamp-black; the figure for wood, plaster and building stone is 0.015, for polished sheet-iron 0.00189, leaded sheet-iron 0.00273, ordinary sheet-iron 0.01164, new cast-iron, 0.01332, oxidised cast-iron 0.01410 (see also Richards "Metallurgical Calculations," Vol. I, Chapter 8).

91. Total heat required. The five items given in Par. 63 represent together the total heat produced, which is partly utilised and partly wasted. This total heat is equal to the electrical energy consumed within the furnace, according to the following relations:

1 watt-hr. = 0.86 kg-cal. = 860 g-cal.,
1 kg-cal. = 1,000 g-cal. = 1.163 watt-hr.

92. The electrical energy is changed into heat by either of the following ways: first, by producing an electric arc and thereby generating heat; or, second, simply by the Joulean effect, the electric energy being changed into heat on account of the electric resistance of the path of the current, the rate of heat produced being I^2R watts or 0.24 I^2R g-cal. per sec., if I is amperes (effective amperes in case of alternating current) and R is ohms (resistance, not impedance). Accordingly, electric furnaces are divided into arc furnaces and resistance furnaces. The material in a resistance furnace in which the electrical energy is changed into heat is called the resistor (FitzGerald). In many cases it is difficult to say whether a furnace belongs to one or the other class, since both effects may be superposed.

CONSTRUCTION AND DESIGN OF ELECTRIC FURNACES

93. A typical arc furnace is shown in Fig. 1 which represents the original furnace of H. Moissan, composed of two blocks of lime placed one on the other. The lower piece had a longitudinal groove through which passed two carbon rods, between which the arc played. In the centre of the lower block below the arc a cavity was provided which served as a crucible or which

* Concerning further details see J. W. Richards, "Metallurgical Calculations," Vol. I, Chapter 8. The flow of heat through contact surfaces is discussed by Carl Hering in *Met. & Chem. Eng'ing*, Vol X. p. 40, where he gives a table of contact resistances in thermal ohms.

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contained a special carbon crucible in which the material to be heated was placed. The upper block was slightly rounded out directly above the arc. By the strong heat of the arc the surface of the lime was fused and highly polished so as to form a perfect reflector sending all the heat down upon the crucible.

94. Direct and indirect arc furnaces. In the former the furnace charge is directly exposed to the arc, in the latter it receives the heat of the arc by radiation and by reflection from the roof and walls. It is clear that in many cases there is combined direct and indirect heating. A typical example of indirect arc heating is the **Stassano furnace.** For operation by three-phase currents, there are three electrodes at the top. The arcs play between the ends of the three electrodes and heat the metallic bath below by radiation (there being no arcs between the electrodes and the bath itself). To mix the charge thoroughly, the furnace is built revolvable. (*Electrochem. & Met. Ind.*, Vol. VI, p. 315.)

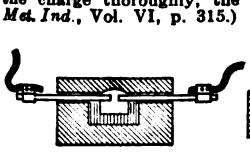


FIG. 1.—Moissan Arc Furnace.

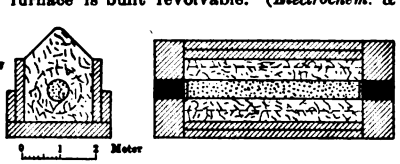


FIG. 2.—Acheson Carborundum Furnace.

95. A typical resistance furnace is the carborundum furnace of E. G. Acheson, shown in plan and vertical section in Fig. 2, the dimensions referring to a capacity of 750 kw. The charge which consists of carbon, silica sand and salt, surrounds a carbon core which acts as resistor and is placed in the centre of the furnace. It runs through the furnace from end to end and is connected at both ends with the carbon terminals or electrodes in the end walls of the furnace. (For further details see F. A. J. FitzGerald, *Electrochem. and Met. Ind.*, Vol. IV, p. 54.) The current through the resistor produces heat which passes outward into the charge, resulting in the production of carborundum.

96. Resistance furnaces may again be **subdivided** according to the nature of the resistor, whether the electric heat is produced in the charge itself or in a special resistor, in contact with the charge. The former is possible only if the charge itself is a conductor of electricity; an example is the induction furnace for melting steel, etc. In case the furnace charge is not itself a conductor of electricity, a special resistor must be provided in contact with the charge; the electricity takes a predetermined path in passing through the resistor in which the heat is thereby developed. An example is the carborundum furnace described above. Finally it is possible to so arrange the resistor that it is not in direct contact with the charge, but is arranged above it and heats the charge by radiation.* Concerning materials suitable for resistors see Par. 111.

No sharp distinction is always possible between the two subclasses of resistance furnaces with or without a special resistor. For instance, in the Acheson furnace for changing carbon electrodes into graphite electrodes, the electrodes are embedded in granular graphite; most of the heat is developed in the latter, but since the electricity also passes through the electrodes themselves, some heat is also directly produced within the same. An example of a furnace operation which changes in character during a run is Acheson's furnace for producing graphite in bulk; in the centre of the anthracite coal, coke, etc., to be graphitized the resistor in form of a series of carbon rods, is placed through which the electricity first passes exclusively; when the anthracite coal next to the core is changed by the heat into graphite, the electricity also passes through it and so on. Therefore, while the electricity had first only a restricted definite path, its path gets broader and broader during operation.

97. Pinch phenomenon. A peculiar limitation of the temperature obtainable in that class of resistance furnaces in which the charge itself forms

*FitzGerald. *Met. & Chem. Eng'ing*, Vol. VIII, p. 317; Vol. IX, p. 29.

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the resistor, is the "*pinch phenomenon*," * described by Carl Hering in the *Transactions* American Electrochemical Society, Vol. XI and XVI.

This same pinch phenomenon is made use of by Carl Hering in his **pinch effect furnace**, † which is a special type of resistance furnace. The charge is contained in a crucible and the current is introduced through electrodes in the bottom, the upper part of which (that is, the part in contact with the charge in the crucible) forms at the same time the resistor. These resistor tubes are so dimensioned that the proper amount of heat is generated in them. At the same time the liquid metal in the resistor tubes is ejected by the pinch effect into the crucible whereby an effective agitation and circulation of the metal in the crucible is obtained.

98. Héroult furnace. An example of an electric furnace which is strictly neither an arc furnace nor a resistance furnace is the steel furnace of P. Héroult. The steel to be purified in the furnace chamber is covered by a layer of slag so chosen as to produce the desired chemical reactions. Two vertical carbon electrodes are suspended through the top of the furnace in

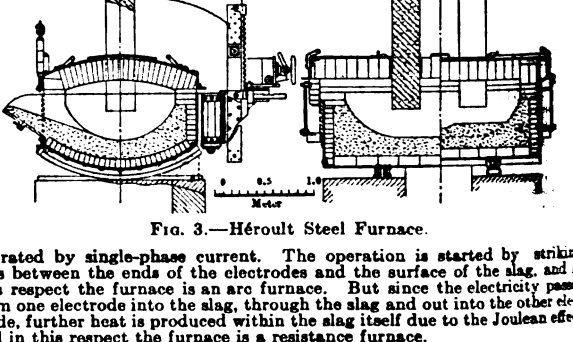


FIG. 3.—Héroult Steel Furnace.

operated by single-phase current. The operation is started by striking arcs between the ends of the electrodes and the surface of the slag, and in this respect the furnace is an arc furnace. But since the electricity passes from one electrode into the slag, through the slag and out into the other electrode, further heat is produced within the slag itself due to the Joulean effect and in this respect the furnace is a resistance furnace.

99. The Girod furnace differs from the Héroult furnace, because it has one or several bottom electrodes, in form of steel rods inserted in the bottom and water-cooled from the outside. There is one or several electrodes at the top, but if more than one is used, they are all electrically connected in parallel (instead of the series connection in the Héroult furnace). The current passes from these top electrodes through the arcs into the slag and downward through the metallic bath and out of the furnace through the bottom electrodes. (*Met. & Chem. Eng'ing*, Vol. IX, p. 581.)

100. The Keller furnace differs from the Girod furnace only in details of the bottom construction. (*Transactions* Am. Electrochem. Soc., Vol. XV.)

101. Loss of energy. Whatever the type of the furnace, the electrical energy which is changed into heat within the furnace itself is less than the electrical energy which must be supplied outside, since the transfer of the energy from the outside into the furnace always involves losses. This transfer of electrical energy may be made either by electromagnetic induction or through terminals, extending through the furnace walls.

102. Induction furnace. An electric furnace into which the electrical energy is transmitted by electromagnetic induction is called an induction

* Formulas for the pinch phenomenon are given by E. F. Northrup, *Phys. Rev.*, Vol. XXIV, p. 474, and C. Hering, *Met. & Chem. Eng'ing*, Vol. IX, p. 86.

† *Met. & Chem. Eng'ing*, Vol. IX, pp. 277, 371.

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furnace. It is essentially a transformer, the secondary of which is a single turn, represented by an annular channel which contains the charge. It is necessarily operated by alternating current which is fed to the primary winding, thus setting up an alternating magnetic flux in the transformer core of laminated iron; this again produces alternating current in the furnace charge in the secondary annular channel, thus heating the charge directly by the Joulean effect. A tilting induction furnace for melting metals (A. E. Colby, F. A. Kjellin) is shown diagrammatically in Fig. 4.

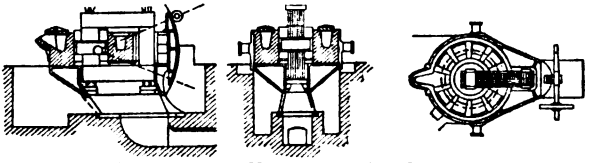


FIG. 4.—Colby-Kjellin Induction Furnace.

The **chief advantage** of this type of furnace lies in the fact that there are no electrodes which could contaminate the bath, so that the chemical composition of the bath can be absolutely controlled by carefully selecting the raw materials. The nature of the atmosphere in which the reaction takes place is also in absolute control of the operator. It is also possible to heat up such a furnace very quickly. (FitsGerald, *Electrochem. & Met. Ind.*, Vol. VII, p. 10, 1909.)

The **losses of energy** in transfer from the primary to the secondary are calculated exactly as in the case of the ordinary transformer (Sec. 6). The induction furnace differs (quantitatively, not qualitatively) from commercial alternating-current transformers, since it has necessarily considerable magnetic leakage fluxes due to the necessity of careful insulation of the fused-bath channel from the primary winding. The **power-factor** is low, due to two causes: the low resistance of the secondary and its high self-induction, due to its wide separation from the primary. The power-factor can be improved by any of the following means: decreasing the frequency of the alternating current, or increasing the ohmic resistance of the fused charge, or increasing the magnetic reluctance of the two leakage fields.

103. The Roechling-Rodenhauser combination furnace is a modification of the simple induction furnace. It is heated by a superposition of two heating effects: firstly, according to the simple induction principle; secondly, an auxiliary secondary circuit is provided, the ends of which are connected to metallic pole plates embedded in the furnace walls. When the furnace is started, it is first heated by induction alone. When the refractory layer which separates the pole plates from the metallic bath thereby becomes hot, it becomes an electric conductor and supplementary heat is now produced by the electric current passing between the pole plates through the furnace charge. The advantages of this furnace over the simple induction furnace are that it can be used for refining (not only melting) purposes and that it can be built with ordinary commercial frequencies for large charges so as to operate with a good power-factor. (*Electrochem. & Met. Ind.*, Vol. VI, pp. 10, 143, 438, 458; *Met. & Chem. Eng'ing*, Vol. VIII, p. 338, Vol. X, p. 263, Vol. XI, pp. 99 and 599; *Transact.* Am. Electrochem. Soc., Vol. XX, p. 293.) Another combination of arc and resistance furnace is the "paragon furnace" (Harden, *Met. & Chem. Eng'ing*, Vol. IX, p. 38, 595).

104. Electrodes. If the electrical energy is introduced into the furnace through terminals, they consist almost always either of amorphous carbon or of graphite, at least for large furnaces. In this country amorphous carbon electrodes are generally made from petroleum coke, while in Europe electrodes made from anthracite coal are also used. However, artificial graphite electrodes made by the Acheson process in the electric furnace, are very extensively employed now. They are more expensive, but can be easily machined into any shape (C. E. Collens, 2nd, *Transactions* of the American Electrochemical Society, Vol. I; *Electrochemical Industry*, Vol. I, p. 26 and Vol. II, p. 277; W. MeA. Johnson, *Electrochemical Industry*, Vol. II, p. 345),

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are more resistant to combustion and have a higher electric conductivity; on the other hand, graphite has also a higher thermal conductivity than amorphous carbon. Electrode holder construction is fully treated in *Met. & Chem. Eng'ing*, Vol. XI, p. 321. Concerning the dimensioning and arrangement of the conductors, carrying the heavy currents to the electrodes, see Randall, *Transact.* Am. Electrochem. Soc., Vol. XVII, p. 139.

105. Loss of heat through electrodes. As mentioned in Par. **69**, the heat loss through an electrode (if the heat insulation to the surrounding walls is assumed to be perfect) can best be considered as the sum of the pure heat conduction loss, due to temperature difference T between the two electrode ends, plus one-half the Joulean heat loss in the electrode itself. For a given current and a given temperature difference T the heat loss through an electrode becomes a minimum if the dimensions of the electrode are so chosen that the Joulean heat loss is twice the pure heat conduction loss; this leads to a simple calculation of the ratio of length to cross-section of the electrode. This rule is rigidly correct if no heat leaks into the walls and if the thermal conductivity and the electrical conductivity of the electrode material are assumed to be independent of the temperature within the temperature limits in the electrode. In this case this is also the condition under which the hot electrode end within the furnace is in temperature equilibrium with the interior of the furnace, no heat passing through the hot electrode end in either direction. For practical applications this method of determining the ratio of length to cross-section can be made independent of any assumption as to the variations of the conductivities, if the ratio of length to cross-section is directly determined by experiments under the conditions of electrode operation. The following figures (C. Hering) give directly for copper, iron, graphite, and carbon those numerical values with which the product of length in centimeters and current in amperes is to be multiplied in order to find the proper or rational cross-section; proper or rational means that under these conditions there will be heat equilibrium at the hot electrode end.

	T = 800 deg. cent.	1000	1200	1400	1600
Copper	0.000036	0.000035	0.000035	0.000035	0.000034
Iron	0.00026	0.00025	0.00025	0.00025	0.00025
Graphite	—	0.00063	0.00059	0.00057	0.00055
Carbon	—	0.00187	0.00162	0.00145	0.00132

	1800	2000	2500	3000 deg. cent.
Copper	0.000034	0.000034	—	—
Iron	0.00025	0.00025	—	—
Graphite	0.00054	0.00053	0.00051	0.00050
Carbon	0.00123	0.00115	0.00102	0.00093

In this table the temperature difference T is given in deg. cent. The figures in the table are given in centimeters per ampere so that when these figures are multiplied by the length in centimeters and the current in amperes, the cross-section is obtained in square centimeters. For instance, the current may be 1,000 amp. and the temperatures of the furnace 2,100 deg. cent., that of the cold electrode end 100 deg. cent., hence the temperature difference 2,000 deg. cent.; further the electrode length may be 25 cm., then the graphite cross-section is $0.00053 \times 1{,}000 \times 25 = 13$ sq. cm. These figures relate, however, only to the "essential part" of the electrode, that is, that part which is embedded in the furnace walls, and are valid if the heat insulation is as good as in the tests in which the above values were determined. Concerning the whole theory see Carl Hering, *Electrochem. & Met. Ind.*, Vol. VII, pp. 442, 473, Vol. VIII, p. 471. *Transactions* Am. Electrochem. Soc., Vol. XVI, pp. 265, 317, and Vol. XVII, pp. 151 and 171, *Proc.* Am. Inst. Elec. Eng., March, 1910; *Met. & Chem. Eng'ing*, Vol. VIII, pp. 128, 188, 276; *Elec. World*, June 16, 1910; C. A Hansen.

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ansactions Am. Electrochem. Soc., Vol. XV, p. 279, Vol. XVI, p. 329, *ectrochem. & Met. Ind.*, Vol. VII, pp. 358, 389; E. F. Roeber, *Transac-ns* Am. Electrochem. Soc., Vol. XVI, p. 363; J. Forssell, *Met. & Chem. g'ing*, Vol. VIII, pp. 26 and 177; A. E. Kennelly, *Proc.* Am. Inst. Elec. g., March, 1910, p. 267.

106. Regulation of the heat production is of greatest importance; is is, of course, identical with regulation of the electric energy supply. arc furnaces this is obtained by adjusting the position of the electrodes, hich may be done either by hand or automatically. A simple automatic ethod in case of a furnace with one electrode, the crucible forming the her terminal, is to control the position of the electrode by an electro-agnetic device, the magnet winding being in shunt with the crucible and e electrode, so that the exciting current of the magnet depends on the current rough the furnace. In the single-phase Héroult steel furnace which has ·o electrodes, there being current from one electrode through the slag to the her electrode, it is important to know that both arcs are playing properly. or this purpose a voltmeter is connected in parallel with each of the elec-odes and the molten furnace charge; one terminal of the voltmeter is nnected with the electrode and the other with some contact in the molten eel charge. Each voltmeter may, of course, be provided with an automatic gulating attachment.

107. In the operation of resistance furnaces it is a fact of great im-rtance that the resistance is a variable quantity during the run of the rnace, both on account of variation of temperature and of the chemical anges in the charge. In order to work economically, it is usually im-rtant that the maximum power available be used throughout the furnace n, and if the resistor changes its resistance it is necessary to provide some eans of regulating the voltage, and the maximum and minimum voltages tainable must have to each other the ratio of the square roots of the aximum and minimum resistance of the resistor (FitzGerald). If carbon used as a resistor, it is advisable to raise it previously to the maximum mperature to which it will be submitted in practice. The best plan is to e graphitised carbon, for that form of carbon is stable in its physical aracteristics so that the only change that is experienced when using it as resistor is temporary and due to the increase in temperature.

108. Direct current and alternating current may both be used for eration of an electric furnace, but alternating current has two advantages: st, electrolytic effects which are not desired in pure electric-furnace reac-ns, are excluded; second, alternating current permits easier regulation. ie induction furnace always requires alternating current.

109. Rheostats. As rheostats for voltage regulation, water rheostats or anular-carbon rheostats are suitable. (For details see F. A. J. FitzGerald, *ectrochemical and Metallurgical Industry*, Vol. III, p. 9).) Rheostat sign, see Sec. 5).

110. Tube furnace. A special type of resistor furnace for experimental ork which permits very exact regulation of temperature, is the tube furnace, ., an electric furnace in which the resistor has the form of a tube. For rious designs of such furnaces see Hutton and Patterson, *Electrochemical id Metallurgical Industry*, Vol. III, p. 455; S. S. Sadtler, *Electrochemical id Metallurgical Industry*, Vol. IV, p. 434; S. A. Tucker, *Electro-emical and Metallurgical Industry*, Vol. V. p. 227; J. A. Harker, *Electro-emical and Metallurgical Industry*, Vol. III, p. 273; William C. Arsem, *ansactions* American Electrochemical Society, Vol. IX; and especially e elaborate designs of H. N. Potter, U. S. Patents, 715507; 715508; 5509; Dec. 9, 1902; 719507, Feb. 3, 1903; 756891, April 12, 1904; '0312, Sept. 20, 1904; 814726 and 814727, March 13, 1906 Tube fur-ces may be so constructed as to carry out the reaction either under in-eased or reduced pressure, as in the furnace of Arsem and the last two itents of Potter.

111. In another special type of resistor furnace, due to FitzGerald id Thomson, the charge is heated by radiation from a resistor above the arge; this furnace has been applied for zinc smelting (*Met. & Chem. g'ing*, Vol. VIII, pp. 289, 317). Various materials are suitable for the resist-s, according to the special design of the furnace, such as granular carbon kryptol"), carbon rods, silundum rods, platinum strip or wire, nickel strip

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or wire, tungsten or molybdenum strips or wire (Winne and Dantsizen, *Transact.* Am. Electrochem. Soc., Vol. XX, p. 287), etc.; an alloy of nickel and chromium has the advantage over pure nickel that it will not oxidize even if heated in air to incandescence for a considerable time ("nichrome").

112. Comparatively simple resistance furnaces for heating crucibles are described by F. A. J. FitzGerald, *Electrochemical and Metallurgical Industry*, Vol. III, p. 55; Oliver P. Watts, *Electrochemical and Metallurgical Industry*, Vol. IV, p. 273; Samuel A. Tucker, *Electrochemical and Metallurgical Industry*, Vol. V, p. 227; D. F. Calhane, *Met. & Chem. Eng'ing*, Vol. X, p. 461; a vertical-arc furnace for laboratory work by Samuel A. Tucker, *Electrochem. and Met. Industry*, Vol. IV, p. 263. A high-temperature laboratory furnace with very exact temperature regulation is described by E. F. Northrup, *Met. and Chem. Eng'ing*, Vol. XII, p. 31.

113. Resistance furnace design and construction. An excellent serial of articles on resistance furnace design and construction was published by F. A. J. FitzGerald in *Electrochemical and Metallurgical Industry*, Vols. II, III, IV. Two papers by F. A. J. FitzGerald, *Transactions* of the American Electrochemical Society, Vol. IV; and by C. L. Collens, 2nd, *Transactions* of the American Electrochemical Society, Vol. IX, deal with the theory of the resistance furnace; a paper by J. W. Richards, *Transactions* of the American Electrochemical Society, Vol. II, with the efficiency of electric furnaces. A serial on electric furnaces, their design, characteristics and commercial applications, for students, engineers, and business men, by W. McA. Johnson and G. N. Sieger appears in *Met. & Chem. Eng'ing*, Vols. XI and XII. Concerning the classical electric-furnace researches of H. Moissan, see his book on the electric furnace which is available for the English reader in an American as well as in the English edition.

114. Reducing agent. It should be emphasized that in an electric furnace the electrical energy provides the heat required for the reaction, but that if the object is **to reduce an element from a compound**, a reducing agent like carbon is also required. For instance, if we compare reduction of iron ore in the electric furnace with the blast-furnace process, both processes require so much carbon as is necessary to combine with the oxygen of the iron oxide; but the blast furnace also requires carbon for producing the necessary high temperature and it is only this last portion of carbon the calorific value of which is replaced by electrical energy in the electric furnace.

115. Carbon as a reducing agent. For most purposes some form of carbon is used as a reducing agent in the electric furnace and it has been claimed that at the temperature of the electric furnace carbon is able to reduce any known oxide.

116. In special cases other reducing agents may be used, especially when the object is to produce metals or alloys for use in the steel industry where it is of advantage to use metals or alloys free from carbon. Such metals and alloys are produced by the **aluminothermic method** of Hans Goldschmidt of reducing a metal from its oxide by means of aluminum; on account of the very high oxidation heat of aluminum the reaction when once started goes on by itself, no outside source of power being necessary, neither fuel nor electrical energy. On account of its strong reducing power aluminum may also be used in electric furnace reactions for special purposes, as is done by A. J. Rossi for production of ferrotitanium (*Electrochemical Industry*, Vol. I, p. 523). Other suitable reducing agents are silicon and carborundum (for instance F. M. Becket, *Electrochemical and Metallurgical Industry*, Vol. V. p. 237, also E. F. Price, for the production of other ferro-alloys). Other reducing agents for special purposes are calcium carbide and metallic calcium.

117. Comparison of electric furnace with coal furnace. Since in an electric furnace electrical energy replaces the heat of combustion of coal in coal-fired furnaces, a numerical comparison of the economy of both processes in this single respect may be given. But it must not be forgotten that this is the most unfavorable way of looking at the economy of the electric furnace, since we purposely ignore all its special advantages.

One kilowatt-hour is equivalent to 860 kg-cal., *i.e.*, the full heat which can be produced from 0.1 kg. of good coal when completely burnt to CO_2. If the cost of 1 ton (2,000 lb. = 907 kg.) of coal is a dollars and if the efficiency of heat production by burning coal is m per cent. then the cost of produc-

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) kg-cal. from burning $\frac{10}{m}$ kg. coal is $\frac{a}{90.7\ m}$ dollars. On the other hand, the cost of 1 kw-hr. is *b* cents and if the efficiency of producing heat m electrical energy is *n* per cent. then the cost of 860 kg-cal. from $\frac{100}{n}$ -hr. is $\frac{b}{n}$ dollars. Hence electric heat will be cheaper than heat pro- ced by combustion of fuel if *an* is greater than 90.7 *bm*.

.17a. A continuous self-baking electrode, invented by C. W. Söder- g, is described by J. W. Richards in a paper read before the Am. Electro- m. Soc. in Boston, April 8, 1920. An iron shell is provided, into the per end of which the ordinary carbon mix is stamped. The lower end is the furnace. As the electrode is consumed, new sections of shell are dded on and new mixture is stamped in. The heat conducted up the ctrode from its lower end slowly bakes the mix in place, the hydrocarbon es being forced to pass downwards through the hot end into the furnace, as depositing carbon therein and consolidating it. The rate of consump- n is always less than is required for baking, so that the mass is baked roughly hard some distance above the furnace. The holder is adjusted es to the furnace, on the baked part of the electrode. The iron casing its away in the furnace. Electrodes up to 85 cm. (34 in.) are already practical use in Norway, and will soon be set up at an American ferro- con plant. The total cost is probably less than half that of using pre- ously baked electrodes, with the advantage of continuity of operation ring the life of the furnace or during a campaign of the furnace. The tents are owned by Detnorsk A. S. for Elektrokemish Industri of Chris- nia, Norway.

COMMERCIAL PRODUCTS OF THE ELECTRIC FURNACE

118. A brief summary of the most important commerical products of e electric furnace will now be given. Concerning the production of rious modifications of carbon (including artificial diamonds) and the pro- ction of chromium, manganese, molybdenum, tungsten, uranium, vana- m, zirconium, as well as carbides, silicides, borides, phosphides, arsenides d sulphides on an experimental scale, see Moissan's "Electric Furnace." A ry useful bibliography on borides and silicides may be found in O. P. Watts, nvestigation of the Borides and the Silicides," Bulletin University of Wis- nsin, No. 145. A. Stansfield's "Electric Furnace" is a reliable and concise scriptive book. Askenasy's "Einführung in die technische Elektrochemie," l. I (Electrothermie) contains valuable information on various electric rnace processes. Concerning new proposed applications of the electric rnace the reader is referred to the current abstracts of new electrochemical tents in *Met. & Chem. Eng'ing.* The following list includes only the st important products which are made in the electric furnace on an in- strial scale.

119. Artificial graphite is made by the processes of E. G. Acheson in ee forms: hard graphite in bulk, suitable for paint, pigment, etc.; artificial aphite electrodes for electric furnace and electrolytic work; soft graphite itable as lubricant, stove polish, etc. See descriptions of the three proc- es in *Electrochemical and Metallurgical Industry*, Vol. III, p. 416 and Vol. , p. 502, Vol. VII, p. 187.
Concerning the conditions of transformation of amorphous carbon into aphite see Arsem, *Trans.* Am. Electrochem. Soc., Vol. XX, p. 105.

120. Silicon Carbide* (trade names carborundum, crystolon) is made the process of E. G. Acheson from a charge of carbon, sand and salt, the ential reaction being $SiO_2+3C=SiC+2CO$. The chief uses of car- rundum are as an abrasive and a refractory.

*Descriptions of the silicon carbide furnace in *Electrochem. & Met. Ind.* l. IV, p. 53; Vol. VII, 189; *Met. & Chem. Eng'ing*, Vol. X, p. 519, 685. ncerning the temperature of the silicon carbide furnace, see Saunders. *et. & Chem. Eng'ing*, Vol. X, p. 287.

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121. Artificial emery or alundum,* another artificial abrasive, is made according to C. B. Jacobs by fusing bauxite in the electric furnace.

122. Aloxite. Another artificial abrasive, aloxite† consisting also principally of fused alumina, is made by an electric furnace process of Tone from aluminum silicate.

123. Siloxicon‡ is a series of silicon-carbon-oxygen compounds of a very refractory nature, made by the process of E. G. Acheson.

124. Metallic Silicon§ is made by the process of F. J. Tone, in which the reaction $SiO_2+2C=Si+2CO$ is used. **Silicon monoxide‖** (monox) was made by the process of Henry Noel Potter. **Silundum¶** is obtained by action of silicon on carbon and is useful as a refractory and resistor.

125. Fused quartz or **fused silica** or **silica-glass** articles are made in the electric furnace by smelting quarts into the desired shape, and are useful since they have such a small temperature coefficient of expansion that they can be subjected to very wide variations of temperature without danger of cracking.

126. Bisulphide of carbon is made from sulphur and carbon by the process of E. R. Taylor (*Electrochemical and Metallurgical Industry*, Vol. I, pp. 60, 63, 70, Vol. IV, p. 32; *Transactions* American Electrochemical Society, Vol. I and II). This is an example of an electric furnace process, the product of which is obtained in vapor form and condensed outside.

127. Zinc is another example of the same class. It has been made in the electric furnace commercially by the process of C. G. P. deLaval.** The chief obstacle in the commercial development of electric zinc smelting has been the difficulty of condensing the zinc vapor into liquid spelter, as almost all early experimenters have been troubled with the production of an excessive amount of blue powder. But this trouble seems now to have been overcome to a large extent. Of American experimenters W. McA. Johnson has gone far gone furthest in commercial operation. Most electric zinc furnaces use carbon as reducing agent, the ore being previously roasted and prepared, the electric-furnace reaction is $ZnO+C=Zn+CO$. In the Imbert process zinc sulphide is reduced by iron as reducing agent, the reaction being $ZnS+Fe=Zn+FeS$. There is a large literature in existence on electric zinc smelting.††

128. Phosphorus is a third example of producing a volatile product. In the Readman-Parker process a mixture of natural phosphate, carbon and sand is treated in a resistance furnace. (*Electrochem. & Met. Ind.* Vol.

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* *Electrochem. & Met. Ind.*, Vol. I, p. 15; Vol. III, pp. 30, 340 and 406. As to the use of alundum as refractory see *Met. & Chem. Eng'ing*, Vol. II, p. 257 (Saunders) and Vol. X, p. 129 (FitzGerald).

† *Electrochem. & Met. Ind.*, Vol. VII, p. 192.

‡ *Electrochem. Ind.*, Vol. I, p. 287; Vol. II, p. 442.

§ Tone, *Electrochem. Ind.*, Vol. II, p. 111 and Vol. VII, p. 192. *Transactions* Amer. Electrochem. Society, Vol. VII, p. 243; Tucker, *Met. & Chem. Eng'ing* Vol. VIII, p. 19. As to the properties of silicon and the use of silicon castings for the chemical industries see *Met. & Chem. Eng'ing* Vol. XI, p. 1

‖ *Electrochem. & Met. Ind.*, Vol. V, p. 444.

¶ Boelling, Tone, Tucker. *Electrochem. & Met. Ind.*, Vol. VII, pp. 24, 1 512.

** F. W. Harbord. *Eng. & Min. Journal*. Feb. 10, 1912, p. 314.

†† Among early literature there are of particular interest a summary by W. McA. Johnson, *Electrochem. & Met. Ind.*, Vol. V, p. 83, also Vol. IV, p. 152 and 321; also two papers by the same author and E. R. Taylor in *Transact.* Am. Electrochem. Soc., Vol. XI; Richards, *Electrochem. & Met. Ind.*, Vol. VI, p. 196; Cote & Pierron, Vol. VII, p. 468. Among recent papers are Johnson, *Met. & Chem. Eng'ing*, Vol. X, pp. 281, 537, Vol. XI, pp. 678; Ingalls, Vol. X, p. 481; Louvrier, Vol. X, p. 747, Vol. XI, pp. 603 and 710; Clerc, Vol. XI, p. 637. Concerning the condensation problem see *Met. & Chem. Eng'ing* Vol. X, p. 451 (an electrolytic method of Bleecker for reduction of blue powder is described in *Transact.* Electrochem. Soc., Vol. XXI, p. 2 See also papers by Johnson, Peterson, Lyon in *Transact.* Am. Electrochem. Soc., Vol. XXIV, and chapter 12 in Stansfield's "Electric Furnace."

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p. 407). Concerning the electric distillation of turpentine from wood F. T. Snyder, *Transactions* Am. Electrochem. Soc., Vol. XIII.

29. Calcium carbide (CaC_2) production is one of the largest and most ortant electric-furnace industries (T. L. Wilson, H. Moissan, L. M. lier). The reaction is

$$CaO + 3C = CaC_2 + CO, \quad (27)$$

furnace charge consisting of burnt lime and ground coke. The chief use alcium carbide is the production of acetylene gas C_2H_2 for lighting, ac- ling to the equation:

$$CaC_2 + H_2O = CaO + C_2H_2, \quad (28)$$

tylene gas being developed when calcium carbide comes into contact h water.* **Calcium cyanamide** is made from calcium carbide and ogen. See Par. **263.**

30. The application of the electric furnace in other branches of n-ferrous metallurgy is partly experimental.† Experiments have been le on electric smelting of copper ores,‡ nickel ores,§ and tin ores.‖ , Elec- furnace smelting of brass is now making great strides.

31. Ferro-alloys,¶ as well as other alloys, like copper-silicon, are made the electric furnace according to the old process of A. H. Cowles, by ting a mixture of pig iron (or copper in the case of copper alloys), an le of the element to be alloyed with the iron (*e.g.*, silica in the case of oilicon) and carbon. Various combinations are possible. The pro- tion of ferro-alloys in the electric furnace is a commercial success; various ys, especially those of high percentage and low in carbon, can only be le in the electric furnace. The usual reducing agent is carbon. But on or ferrosilicon or carborundum have also been proposed for the duction of other ferro-alloys, free from carbon.

32. In the steel industry** the electric furnace is rapidly increasing mportance for three purposes. The first†† is the manufacture of high- le steel in competition with the crucible steel process, being considerably aper on account of larger units and smaller wages, while the product of electric furnace is as good as that of the crucible steel process and it is necessary to use as pure and expensive starting materials. The second lication‡‡ is a more recent one, for the refining of molten Bessemer con- er metal or molten open-hearth metal for large-tonnage products, like s of improved quality. For steel refining in the electric furnace the pos- lity of producing a higher temperature in the slag§§ is important, but of

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Concerning the thermodynamic theory of the process see Thompson, . *& Chem. Eng'ing*, Vol. VIII, pp. 279 and 324.

Concerning possible applications of the electric furnace to Western allurgy, see Lyon and Keeney, *Met. & Chem. Eng'ing*, Vol. XI, p. 577. to vacuum furnace metallurgy for the treatment of rebellious ores, such sulphite, Nipissing ore, for the production of antimony from stibnite, Fink, *Met. & Chem. Eng'ing*, Vol. X, p. 296. As to the use of the elec- furnace for the treatment of tin dross concentrates from cyanide ls, etc., see Wile, *Met. & Chem. Eng'ing*. Vol. X, p. 495.

Stephan, *Met. & Chem. Eng'ing*, Vol. XI, p. 22; Lyon and Keeney, Vol. , p. 522.

Morrison. *Transact.* Am. Electrochem Soc., Vol. XX, p. 315.

Harden. *Met. & Chem. Eng'ing*, Vol. IX, p. 453.

G. P. Scholl. *Electrochem. Ind.*, Vol. II, pp. 349, 395, 449; Keeney, *nsact.* Am. Electrochem. Soc., Vol. XXIV, p. 167. Concerning ferro- on see Pick and Conrad's German monograph, also Copeman, Bennett Hake, *Met. & Chem. Eng'ing*, Vol. VIII, p. 133.

* A very good review of the situation in 1909 may be found in the sym- ium of papers on the electrometallurgy of iron and steel in *Transact.* Am. ctrochem. Soc., Vol. XV. See also Eugene Haanel's first Canadian vernment report of 1904, and Neumann's Electrometallurgie des Eisen.

† For instance, *Met. & Chem. Eng'ing*, Vol. VIII, p. 563.

‡ Description of South Chicago plant of the U. S. Steel Corporation, t. *& Chem. Eng'ing*, Vol. VIII, p. 179. See also Walker, *Met. & Chem. g'ing*, Vol. X, p. 371, and Osborne, *Transact.* Am. Electrochem. Soc., . XIX, p. 205.

§ As to the function of slag see Amberg, *Met. & Chem. Eng'ing*, Vol. X, 501.

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greater importance seems the neutral or reducing atmosphere since it permits chemical reactions which are impossible in open-hearth furnaces (removal of sulphur as calcium sulphide, removal of phosphorus as phosphide). The cost of refining steel in the electric furnace depends on the composition of the starting material and the degree to which the impurities are to be eliminated, but is relatively small, if the steel to be refined is supplied to the electric furnace in molten state from a Bessemer converter or open-hearth furnace. The third large application* is the use of the electric furnace for making castings. The following furnaces are employed for these three purposes on a commercial scale: Héroult (**98**), Girod (**99**), Stassano (**94**), Roechling-Rodenhauser (**103**), Groenwall†, Nathusius‡ besides some others on a smaller scale. Special smaller applications of electric furnaces in the steel industry are the melting of ferro-manganese§ and the heating of bars and billets.‖

133. Iron reduction¶ in the electric furnace is economical only in the localities where electric energy is cheap and fuel expensive. According to Harbord, when electrical energy is available at $10 per electric horsepower year and coke costs $7 per ton, the cost of production of pig iron in the electric furnace is approximately the same as the cost of producing it in a modern blast furnace. On the other hand the electric furnace has distinct advantages. Ores can be treated in it which could not be economically worked in the past. Ores of high-sulphur content can be made into pig iron containing only a few thousandths of a per cent. of sulphur. Titaniferous iron ores containing up to 5 per cent. can be successfully treated. The silicon content can be varied as required for the class of pig to be produced. As reducing agent it is not necessary nor advisable to employ coke, since charcoal and peat-coke can be satisfactorily used.

134. "Pig Steel" (a metal with 2.2 or less per cent. of carbon, a very small amount of silicon and manganese, low in sulphur and phosphorus) can be produced directly from ore in the electric furnace.** Commercial success has been obtained with iron reduction in electric shaft furnaces in Scandinavia†† and in California.‡‡

ELECTROLYTIC PROCESSES

135. The characteristic feature of an electrolytic process is that chemical oxidation (or perduction) at the anode and the chemical reduction at the cathode; the anode being that electrode through which the (positive) electricity enters the electrolyte, and the cathode that electrode through which it leaves. The result of an electrolytic process is, therefore, a chemical change in the electrolyte, different products appearing at the two electrodes. The contact surfaces between the two electrodes and the electrolyte are the only places at which oxidation and reduction take place. The relation between the quantity of the chemical change and the quantity of electricity passing through the cell is given by Faraday's law as explained in **16** to **37**. Electrolytic processes essentially require direct current.

136. The chief distinction between electric conductors of the first class or **metallic conductors** and electric conductors of the second class or **electrolytes** is brought out if we form an electric circuit of any number of metallic conductors and electrolytes in series and see what happens at the different boundary surfaces. At the junction of two metallic conductors

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* *Met. & Chem. Eng'ing*, Vol. X, pp. 54, 600, 663; Vol. XI, p. 709.

† *Met. & Chem. Eng'ing*, Vol. IX, p. 573.

‡ *Met. & Chem. Eng'ing*, Vol. X, p. 227.

§ *Met. & Chem. Eng'ing*, Vol. IX, pp. 575 and 640 and May, 1914.

‖ Bailey. *Met. & Chem. Eng'ing*, Vol. IX, p. 262 and Vol. X, p. 291.

¶ The most important early literature on the subject comprises E. Haanel's second and third Canadian Government reports, also papers by Haanel, Bennie, Lyon, Richards, in *Transact.* Am. Electrochem. Soc., Vol. XV.

** Richards. *Met. & Chem. Eng'ing*, Vol. X, p. 397 and p. 539.

†† *Met. & Chem. Eng'ing*, Vol. VIII, p. 11; Vol. IX, pp. 368, 459, 505, 630; Vol. X, p. 413; Vol. XII, p. 82; *Transact.* Am. Electrochem. Soc., Vol. XV, p. 375.

‡‡ *Met. & Chem. Eng'ing*, Vol. XI, p. 383; see also Vol. X, pp. 457, 533, 587 and Vol. XI, p. 15.

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ere is nothing but a heat effect. At the junction of a metal and an elec-
olyte there is either chemical adduction or reduction according to the
rection of the current. At the junction of two electrolytes there is neither
duction nor reduction, though there may be a chemical change (*e.g.*, at the
nction of NaCl and KOH, if the current is directed from the former to
e latter, there will be formation of NaOH).

137. The most important electrolytes for industrial applications are:
st, **solutions**, and especially aqueous solutions or solutions in water, and
:ond, **fused salts.**

138. Cells. An electrolyte with two electrodes represents either a
lvanic cell, *i.e.*, an electrochemical system through which a current will be
luntarily established when the two electrodes are electrically connected
rough an outside circuit (in other words an electrochemical system which
n be used as a source of electricity), or an **electrolytic cell**, *i.e.*, an elec-
ochemical system through which an electric current will be established if
e outside circuit connected to the two electrodes contains a sufficiently
:ong source of electrical energy.

139. Galvanic cells. In the case of a galvanic cell or battery the **energy**
uation written on the basis of Thomson's rule states that the chemical
ergy consumed in the cell is partly lost in form of Joulean heat within
e cell ($I^2R \times$time) the balance being available in form of electrical energy
the outside circuit between the terminals of the cell. If this energy equa-
on, the symbols of which represent gram-equivalents, is divided by 96,540
ulombs, *i.e.*, the electric charge of 1 gram-equivalent, the voltage equation
obtained which states that the electromotive force of the cell in volts equals
e loss of the volts within the cell due to internal resistance (IR), plus the
ltage available at the terminals of the cell. This is correct for a mono-
lent change. If the change of valency is n, the energy equation is to be
vided by $96{,}540 \times n$.

140. Electrolytic cells. In the case of an electrolytic cell through
hich electricity is forced from the outside, the energy equation states that
e electrical energy impressed upon the cell at its terminals from the outside
partly changed into the chemical energy required for the chemical process
the cell and partly changed into Joulean heat ($I^2R \times$time). In many
ses, when the process requires an elevated temperature, especially in the
:ctrolysis of fused salts, this evolution of Joulean heat serves a useful
rpose, since it is the easiest way of providing the requisite high temperature
s in the Bradley "internal heating" patent of the aluminium process).
ie corresponding voltage equation states that the voltage impressed at
e terminals of the cell from the outside equals the electromotive force
quired for the chemical reaction according to Thompson's rule plus the
lts lost in the cell due to internal resistance.

141. The model of migrating ions is a picture of electrolytic phenomena
is a dynamical model which has been found exceedingly useful to illus-
ate what happens in an electrolytic cell. Any electrolyte contains
sitive ions or cations and negative ions or anions.

142. Typical anions are:
(a) **monovalent** (each gram-ion carrying a negative charge of 96,540
ulombs):

Br	in hydrobromic acid and bromides,
Cl	in hydrochloric acid and chlorides,
I	in hydriodic acid and iodides,
Fl	in hydrofluoric acid and fluorides,
OH	(hydroxyl ion) in hydroxides or hydrates,
BrO_3	in bromic acid and bromates,
ClO_3	in chloric acid and chlorates,
IO_3	in iodic acid and iodates,
NO_3	in nitric acid and nitrates,
CN	(cyanogen radical),
CHO_2	in formates,
$C_2H_3O_2$	in acetates.

(b) **bivalent** (each gram-ion carrying a negative charge of $2 \times 96{,}540$
ulombs):

SO_4	in sulphates,

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SiO_3 in silicates,
CO_3 in carbonates,
C_2O_4 in oxalates,
CrO_4 in chromates,

143. Typical cations are:
(a) **monovalent** (each gram-ion carrying a positive charge of 96,500 coulombs):
H, K, Na, Cu (in cuprous compounds), Li, Ag, Hg (in mercurous salts)
(b) **bivalent** (each gram-ion carrying a positive charge of $2 \times 96,500$ coulombs);
Cu (in cupric compounds), Fe (in *ferrous* compounds), Zn, Ba, Ca, Pb (in usual or plumbic salts), Cd, Co, Mg, Mn (in manganous salts), Ni (in nickelous salts), Sn (in stannous compounds), Hg (in mercuric salts).
(c) **trivalent** (each gram-ion carrying a positive charge of $3 \times 96,500$ coulombs):
Al, Cr (in chromic salts), Fe (in ferric compounds), Au (in auric salts), Mn (in manganic salts), Ni (in nickelic salts).
(d) **tetravalent** (each gram-ion carrying a positive charge of $4 \times 96,500$ coulombs):
Sn (in stannic compounds).

144. Example. In a solution of hydrochloric acid, HCl, in water the anions are Cl' and the cations $H^{\cdot}$ and according to the picture of migrating ions free hydrogen gas is set free at the cathode and free chlorine gas is set free at the anode, because as a result of the migration of the ions in opposite directions through the electrolyte, an excess of positively charged $H^{\cdot}$ ions appears at the cathode and an excess of negatively charged Cl' ions appears at the anode (while at any place inside of the electrolyte there are always the same number of $H^{\cdot}$ and Cl' ions, hence no excess of positive over negative or of negative over positive ionic charges). The excess of $H^{\cdot}$ ions at the cathode gives off its positive charges to the cathode, while simultaneously the excess of Cl' ions gives off its negative charges to the anode or (what is electrically the same) takes over from the anode an equal amount of positive electricity in order to neutralise the negative ionic charges. Hence, according to this view the maintenance of an electric current through an electrolyte is performed by the migrating ions which transport the electricity both through the electrolyte, and the chemical reduction and oxidation at the two electrodes, being essentially a discharge of the ions, is the necessary consequence of the electricity entering into the electrolyte from the anode and leaving the electrolyte into the cathode. As another example of the application of the model of ions the **electrolytic theory of the corrosion of iron** may be mentioned (Whitney, Cushman, Walker). According to this theory the surface of commercial iron and steel is not of absolutely uniform composition, on account of the presence of particles of slag, manganese oxide, etc., irregularly distributed in the iron. In contact with a solution some spots of the iron surface will tend to become anodes and other spots cathodes, forming short-circuited galvanic cells. Iron then goes into solution from the anodic spots as ferrous ions and hydrogen ions are discharged at the cathodic spots. The fundamental primary reaction is therefore $Fe + 2H^{\cdot} = Fe^{\cdot\cdot} + H_2$. The ferrous ions are then oxidised to ferric by the oxygen of the air. The loose colloidal ferric hydroxide moves towards the cathode under the influence of the current and piles up in the form of rust. (Cushman and Gardner's book on "Corrosion and Preservation of Iron and Steel.")

145. Mobility. In working out the above model in greater detail a certain mobility is assigned to each ion. All the ions pass along the lines of electric force which extend through the electrolyte from one electrode to the other; and the speed with which they travel is directly proportional to the force at any point, *i.e.*, to the potential drop in volts per unit of length (or the differential quotient of the potential taken along the line of electric force through that point). The constant of proportionality is called the mobility, so that **speed of migration** of an ion equals mobility multiplied by potential drop per unit of length of electric line of force. We will designate the mobility of positive ions by u and those of negative ions by v. (Concerning the geometrical configuration of the electric lines of force from one electrode to the other, see M. U. Schoop, *Electrochemical and Metallurgical Industry*, Vol. IV, pp. 268 and 307.)

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146. The method of determining the mobilities, u and v, separately sists in determining their sum and their ratio. According to Faraday's if q coulombs pass through a cell, $\frac{q}{96{,}540}$ positive monovalent gram-ions $\frac{q}{2\times 96{,}540}$ positive bivalent gram-ions, etc.) are concerned in the re- tion at the cathode and the same number of negative gram-ions in the dation at the anode. According to the picture of migrating ions this ans that when q coulombs pass, the sum of the number of positive mono- ent gram-ions passing through any imaginary cross-section of the cell ard the cathode and of the number of negative monovalent gram- s passing through the same cross-section in the opposite direction is $\frac{q}{540}$.

147. Conductivity proportional to the sum of the mobilities. other words, when there is a current of i amperes through an electrolytic l, the sum of the numbers of positive and negative monovalent gram-ions sing per sec. in opposite directions through any imaginary cross-section the cell is $\frac{i}{96{,}540}$. This sum of the numbers of positive and negative am-ions passing per sec. is, of course, directly proportional to the sum of eir speeds or to the voltage drop per unit length of electric line of force ltiplied by the sum of their mobilities. Hence, the sum of the mobilities, $-v$, is proportional to the current in amperes divided by the voltage drop, nce proportional to the conductance and also proportional to the con- ctivity of the electrolyte.

148. Constant of proportionality. The statement that $u+v$ is pro- rtional to the conductivity will now be supplemented by finding the nstant of proportionality. For this purpose we necessarily need a further pothesis as to the number of ions we have to assume for a given number molecules.

149. Equivalent ionic concentration. Formerly it was silently as- med that in a fused salt all the molecules of the salt participate equally in e transport of electricity, while in the case of solutions the solvent (for stance, water) was assumed to be inert, and all the molecules of the solute ie dissolved salt) were assumed to participate equally in the transport of ctricity. Hence for a fused salt the equivalent ionic concentration is defined as the number of positive monovalent gram-ions per c.c. number of negative monovalent gram-ions per cu. cm. = number of am-molecules of the fused salt multiplied by valency per cu. cm. For solution the equivalent ionic concentration was defined as the number positive monovalent gram-ions per cu. cm. = number of negative mono- lent gram-ions per cu. cm. = number of the gram-molecules of dissolved lt per volume multiplied by valency per cu. cm.

150. Dissociation theory. For fused salts our conceptions have not yet en decidedly changed, while a decided change has been brought about for lutions by Arrhenius' electrolytic dissociation theory. According to him ly a certain number of the dissolved salt molecules are ionized and only ese are active in the transport of the electricity, while the non-ionized solved salt molecules, like the molecules of the solvent, are electrically ert. If we write i for the ratio of the number of ionized molecules to the tal number of dissolved molecules where i is smaller than unity, the equiva- nt ionic concentration is defined as the number of positive monovalent am-ions per cu. cm. = number of negative monovalent gram-ions per cu. cm. ic, where c is the number of gram-equivalents of dissolved salt per cu. cm.

151. Universal formula for use in calculations. We render our lculations general by using the factor i. For fused salts we have to make = 1, while for solutions we are free to take our choice. If we make $i = 1$, e follow the old conception, while if we make i smaller than unity we are on ie basis of the electrolytic dissociation theory. For a given fused salt of iiform constitution, c, has a fixed value depending on the density, while for solution c is variable according to the degree of concentration. As can be sily shown, in the statement that conductivity is proportional to the sum of obilities, the constant of proportionality has the value $96{,}540\,i\,c$. In other

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words, conductivity = 96,540 ic $(u+v)$. This is generally true if we accept the model of travelling ions, and is not dependent on the electrolytic dissociation theory. If we do not wish to accept the latter, we have simply to write $i = 1$.

152. Equivalent conductivity is defined as conductivity divided by concentration in gram-equivalents per cu. cm. It may be calculated from measurements of the conductance of a cylinder of cross-section, a, and length, l, through which the current has the direction l. For solutions the number of gram-equivalents per cu. cm. is a variable quantity we may establish this experimentally by using as our cylinder a vertical rectangular trough into which we place a solution of a certain concentration which fills the trough to a certain height, and then add more and more solvent (*e.g.*, water). The length, l, of our cylinder remains thereby constant, while the cross-section, a, is varied simultaneously with the number of gram-equivalents of solute per cu. cm. The latter equals the number of dissolved gram-equivalents (which is held constant in this experiment) divided by the volume $l\,a$ (which is varied, since a is varied). Hence in this experiment the conductance of the solution in the trough equals

$$\times \text{conductivity} = \frac{\text{equivalent conductivity} \times \text{dissolved gram equivalents}}{l^2}$$

This equation is correct whatever may be the dimensions of the trough whose conductance is measured and whatever may be the number of gram-equivalents dissolved. In the special case, that $l = 1$ cm. and the trough contains a solution of 1 gram-equivalent of solute in a variable quantity of water, the conductance is numerically directly equal to the equivalent conductivity. For this reason the equivalent conductivity is often defined as the conductance of a solution containing 1 gram-equivalent of the solute, when placed between parallel electrodes 1 cm. apart.

153. Equivalent conductivity and dilution. From very extended measurements, by F. Kohlrausch, it appears that as a general rule when a solution is gradually more and more diluted, the conductivity decreases but the equivalent conductivity increases and gets nearer a definite constant value for infinite dilution. This is clearly shown in Par. **156** which contains among other results the most recent ones obtained by Kohlrausch and which are reproduced from M. Le Blanc, W. R. Whitney and J. W. Brown's "Text-book of Electrochemistry." Doubtful values in Par. **156** are given in parentheses.

154. Table of values of equivalent conductivities. In Par. **156** the figures represent equivalent conductivities, *i.e.*, conductivities in mhos per cu. cm. (or described more properly in ohms^{-1} cm^{-1}), divided by concentration in gram-equivalents per cu. cm. This table enables one to find easily the conductivity at different concentrations. For instance, we want to find the conductivity of a solution of hydrochloric acid containing 1 gram-equivalent or 36.5 g. HCl per liter (about 3.6 per cent. acid). According to Par. **156** the equivalent conductivity, as just defined, is 301 the concentration is 0.001 gram-equivalent per cu. cm.; hence the conductivity is 0.301 ohms^{-1} cm^{-1}. The conductance of 1 cu. cm., HCl, is therefore 0.301 mhos; that of 1 liter = 3.01 mhos. In both cases the volume is assumed to be in cubic form and the conductance is measured between opposite sides.

155. Concentration. It will be noted that in the figures of concentration given in the first column (Par. **156**) the concentration is defined as gram-equivalents per liter because this is the usual method in practice. On the other hand in the definition of equivalent conductivity we follow Kohlrausch who is responsible for the whole matter and who, in order to remain on the basis of the centimeter gram-second system defines concentration as gram-equivalents per cu. cm. This should be taken into consideration in the use of the table. A solution containing 1 gram-equivalent per liter is called a "normal" solution; a solution containing 0.1 gram-equivalent per liter is called 0.1 normal, etc.

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Gram-equivalents per liter	KCl	NaCl	KNO_3	$AgNO_3$	$\frac{1}{2}CuSO_4$	$\frac{1}{2}H_2SO_4$	HCl	CH_3COOH	KOH	NH_3	Liters in which gram-equivalent is dissolved
0.0001	129.07	108.10	125.50	115.01	109.95			107.		(66)	10000.
0.0002	128.77	107.82	125.18	114.56	107.90			80.		53.	5000.
0.0005	128.11	107.18	124.44	113.88	103.56	(368)		57.		38.0	2000.
0.001	127.34	106.49	123.65	113.14	98.56	361.	(377)	41.		28.0	1000.
0.002	126.31	105.55	122.60	112.07	91.94	351.	376.	30.2	(234)	20.6	500.
0.005	124.41	103.78	120.47	110.03	80.98	330.	373.	20.0	(233)	13.2	200.
0.01	122.43	101.95	118.19	107.80	71.74	308.	370.	14.3	230.	9.6	100.
0.02	119.96	99.62	115.21		62.40	286.	367.	10.4	228.	7.1	50.
0.05	115.75	95.71	109.86	99.50	51.16	253.	360.	6.48	225.	4.6	20.
0.1	112.03	92.02	104.79	94.33	43.85	225.	361.	4.60	219.	3.3	10.
0.2	107.96	87.73	98.74		37.66	214.	342.	3.24	213.	2.30	5.
0.5	102.41	80.94	89.24	77.5		205.	327.	2.01	206.	1.35	2.
1. (normal)	98.27	74.35	80.46	67.6	25.77	198.	301.	1.32	197.	0.89	1.
2.	92.6	64.8	69.4			183.0	254.	0.80	184.	0.589	0.5
3.	88.3	56.5	(61.3)			166.8	215.0	0.54	160.8	0.532	0.33
5.		42.7				135.0	152.2	0.285	140.6	0.364	0.2
									105.8	0.202	

Doubtful values are given parentheses.

157. The increase of equivalent conductivity with increasing dilution may be interpreted in different ways on the basis of the picture of migrating ions. Since conductivity $= 96{,}540\ i\,c\,(u+v)$, equivalent conductivity $= 96{,}540\ i\ (u+v)$.

First, according to the old view, all dissolved gram-equivalents participate equally in the transport of the electricity and $i = 1$; hence equivalent conductivity $= 96{,}540\ (u+v)$. Since the equivalent conductivity increases with increasing dilution, we must assume that the sum of the mobilities simultaneously increases.

Secondly, according to Arrhenius' electrolytic dissociation theory, u and v do not change, but the degree of ionization i changes with dilution. With increasing dilution, i must be assumed to increase until for infinite dilution it reaches a certain definite value. i is the ratio of the number of ionized molecules to the total number of dissolved molecules. For infinite dilution $i = 1$, *i.e.*, all molecules are ionized. The less the dilution or the higher the concentration, the smaller is i, *i.e.*, the smaller the degree of ionization or the smaller the proportion of dissolved gram-equivalents which are ionized.

158. Conductivity of electrolytes. Concerning the measurement of the conductivity of electrolytes see Kohlrausch and Holborn's "Leitvermögen der Elektrolyte." This book contains an enormous amount of detailed information and of figures of conductivities of aqueous solutions. Concerning fused electrolytes see R. Lorens' "Electrolyse geschmolsener Salze," 3 volumes (figures of conductivities in Vol. II).

159. Determination of the ratio of u to v. From Faraday's law and

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from conductivity measurements it is only possible to determine the sum $u+v$, but not u or v separately. This becomes possible, however, for solutions, since from the concentration changes occurring at the electrodes (besides the chemical changes of reduction and oxidation) it is possible to calculate the ratio of the mobility, u, of the cation to the mobility, v, of the anion, as was shown by Hittorf.

The ratio v to $u+v$ is called the transport number or transference number n of the anion, the ratio u to $u+v$ is that of the cation $=1-n$. Tables of transport numbers may be found in any text-book on theoretical chemistry. They were determined experimentally from concentration changes at the electrodes. Conversely we will now show how it is possible to predict concentration changes from the knowledge of the transport numbers.

Let us assume a monavalent solution, or in case of bivalent, etc., solutions let us consider gram-equivalents. Then if $96{,}540q$ coulombs pass through the solution, there is reduction of q gram-equivalents at the cathode and adduction of q gram-equivalents at the anode. Through any arbitrary cross-sectional plane in the centre of the electrolyte nq gram-equivalents of the anion pass toward the anode and $(1-n)\ q$ gram-equivalents of the cation toward the cathode. In the anode compartment, right at the anode, q gram-equivalents of the anion are adduced and form something new (what depends on the special case) and besides this there is due to ionic import and export, a gain of nq anions and a loss of $(1-n)\ q$ cations. There is, therefore, a combined effect, that of adduction at the anode and that of ionic migration. At the cathode q gram-equivalents of the cation are reduced and form something new and, besides this, there is on account of ionic import and export, a gain of $(1-n)\ q$ cations and a loss of nq anions. Here we have also the combined effect of reductions at the cathode and of ionic migration.

160. Numerical example. As a numerical example we will first consider the electrolysis of hydrochloric acid, HCl, with platinum electrodes, the transport number of the anion, Cl being assumed to be $n=0.2$, when 96,540 coulombs pass, 1 gram-equivalent H (1 g) is set free at the cathode and 1 gram-equivalent Cl (35.5 g.) is set free at the anode, both hydrogen and chlorine being set free as gases. From Par. 159 we see that 0.2 gram-equivalent HCl (7.3 g) are lost at the cathode and 0.8 gram-equivalent HCl (29.2 g.) are lost at the anode. The whole phenomenon is this: 36.5 g of HCl disappear by decomposition and the solution becomes diluted both at anode and cathode, but more quickly at the anode. The decomposed 36.5 g. HCl appear in form of 35.5 g. Cl gas at the anode and 1 g. H gas at the cathode.

The safest way in any case is to write down the equation of the whole process, interpret it by the picture of migrating ions, divide the cell arbitrarily into two compartments by a cross-section and calculate separately what happens in the anode and cathode compartments. In the foregoing example, when 96,540 coulombs pass, 0.2 gram-ion Cl passes our arbitrary cross-sectional plane in the direction to the anode and 0.8 gram-ion H in the direction to the cathode. Hence in the anode compartment we have

loss, by setting free as gas, of 1 gram-atom Cl,
loss, by ionic export to cathode compartment, of 0.8 gram-ion, H,
gain by ionic import from cathode compartment of 0.2 gram-ion Cl.

Hence the total result in the anode compartment is the evolution of 1 gram-atom = 35.5 g. Cl and a loss, from the solution, of 0.8 gram-molecule HCl (29 g.). This is the same result as above.

161. As another example we give the electrolysis of an aqueous solution of common salt, NaCl, with an inert anode and inert cathode, such as used in a diaphragm cell. When 96,540 coulombs pass, the reaction is represented by the following equation, all symbols representing atoms:

$$NaCl + H_2O = \underbrace{Cl}_{\text{at anode}} + \underbrace{NaOH + H}_{\text{at cathode}} \qquad (1)$$

If we take the transport number of the Cl ion in NaCl as 0.6, then during the passage of 96,540 coulombs there passes 0.6 Cl gram-ion through any arbitrary cross-section toward the anode and 0.4 Na gram-ion toward the cathode. In the anode compartment we have, therefore;

loss, by gas evolution at anode, of 1 gram-ion Cl
gain, by ionic import from cathode compartment, of 0.6 gram-ion Cl
loss, by ionic export into cathode compartment, of 0.4 gram-ion Na

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net result in the anode compartment is the setting free of 1 gram-atom as and the loss in solution of 0.4 gram-molecule NaCl.

the cathode compartment we have;

by gas evolution at cathode, of 1 gram-ion H,
by ionic export to anode compartment, of 0.6 gram-ion Cl,
by ionic import from anode compartment, of 0.4 gram-ion Na,
by chemical formation of NaOH of 1 gram-ion OH,
by the same reaction, of 1 gram-molecule H_2O.

ne net result in the cathode compartment is the setting free of 1 gram- H gas, the loss in solution of 1 gram-molecule of water, while the e NaCl has now been changed into a mixture of NaCl and NaOH the positive ions have been increased by 0.4 Na gram-ions, while the tive ions have gained 1 OH gram-ion and lost 0.6 Cl gram-ion. This r change we may chemically express in the statement that 0.6 gram cule NaCl have disappeared and 1 gram-molecule NaOH has been ed. (For a somewhat different and more detailed discussion of this ion see W. H. Walker, *Transactions* American Electrochemical ty, Vol. III, p. 177.)

162. Migration Mobilities of Cations

	u_{18}	α	β
H	318.	+0.0154	−0.000033
K	64.87	.0220	+ .000075
Na	43.55	.0245	.000116
Li	33.44	.0261	.000142
Rb	67.6	.0217	.000069
Cs	68.2		
NH_4	64.4	.0223	.000079
Tl	66.00		
Ag	54.02	.0231	.000093
½ Ba	55.10	.0239	.000106
½ Sr	51.54	.0231	.000093
½ Ca	51.46		
½ Mg	45.94	.0255	.000132
½ Zn	46.57	.0256	.000133
½ Cd	47.35		
½ Cu	47.16	.0240	.000107
½ Pb	61.10	.0244	.000114

163. Migration Mobilities of Anions

	v_{18}	α	β
OH	174.	+0.0179	+0.000008
F	46.64	0.0232	.000094
Cl	65.44	.0215	.000067
Br	67.63		
I	66.40	.0206	.000052
SCN	56.63		
ClO_3	55.03	.0207	.000054
BrO_3	46.2		
IO_3	33.87	.0233	.000096
NO_3	61.78	.0203	.000047
ClO_4	64.7		
IO_4	47.7		
MnO_4	53.4		
CHO_2	46.7		
$C_2H_3O_2$	35.0	.0236	.000101
$C_3H_5O_2$	31.0		
$C_4H_7O_2$	27.6		
$C_5H_9O_2$	25.7		
$C_6H_{11}O_2$	24.3		
½ $(COO)_2$	62.6		
½ SO_4	68.14	.0226	.000084
½ CrO_4	72.0		
½ CO_3	60.0	.0269	.000155

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164. Electrolysis may change the original electrochemical system. This last fact is of great importance for many electrolytic processes. It emphasizes the fact that electrolysis may change the original electrochemical system. In the present case we have no longer a pure NaCl solution at the cathode, since it is now mixed with NaOH, *i.e.*, it contains Na^+ and OH' ions, and the OH' ions will begin to travel toward the anode together with the Cl' ions and make trouble there.

165. Determination of the mobilities, u and v, separately. From $u+v$ as determined by equivalent conductivity measurements, and from $u \div v$ as found from Hittorf's transport numbers, Kohlrausch calculated the mobilities, u and v, separately. For infinitely dilute solutions he found the following important law: Any ion of a given chemical nature has a certain distinct mobility which is always the same whatever may be the other ions which are with it in solution; that is, for instance, the mobility, u, of Na in NaCl has the same value as in NaOH, etc. This is **Kohlrausch's law of the independent migration of the ions**, which foreshadowed to a certain extent the electrolytic dissociation theory. In Par. **162** the latest values of the migration velocities, u, of cations are given, in Par. **163**, those of anions together with their temperature coefficient. The figures under u_{18} and v_{18} relate to temperature of 18° C. For a temperature t, not very far from 18 deg. cent., the mobility is,

$$u_t = u_{18}\,[1+\alpha(t-18)+\beta(t-18)^2]. \qquad (31)$$

The table of ionic mobilities is often useful for determining the transport numbers

$$n = \frac{v}{u+v} \text{ and } 1-n = \frac{u}{u+v} \qquad (32)$$

but it must be taken into consideration that the values u and v, in Par. **161** and **163** relate to infinitely dilute solutions. Anyway, they offer a means for approximately finding or checking transport numbers in many cases.

166. Electrochemical Equivalents of Ions

Anions	Milligrams per coulomb	Grams per ampere-hour	Cations	Milligrams per coulomb	Grams per ampere-hour
Br'	0.828	2.982	$Ag^{\cdot}$	1.118	4.025
BrO_3'	1.326	4.772	$Al^{\cdot\cdot\cdot}$	0.0936	0.3369
Cl'	0.3672	1.322	$As^{\cdot\cdot\cdot}$	0.2590	0.932
ClO_3'	0.864	3.112	$Au^{\cdot\cdot\cdot}$	0.681	2.451
CHO_2'	0.4662	1.678	$Ba^{\cdot\cdot}$	0.712	2.562
$C_2H_3O_2'$	0.611	2.201	$Ca^{\cdot\cdot}$	0.2077	0.748
CN'	0.2694	0.971	$Cd^{\cdot\cdot}$	0.582	2.096
CO_3''	0.3108	1.119	$Co^{\cdot\cdot}$	0.3056	1.100
C_2O_4''	0.4558	1.641	$Cr^{\cdot\cdot\cdot}$	0.1799	0.648
CrO''	0.601	2.165	$Cu^{\cdot}$	0.659	2.372
F'	0.1968	0.709	$Cu^{\cdot\cdot}$	0.3294	1.186
I'	1.315	4.735	$Fe^{\cdot\cdot}$	0.2895	1.042
IO_3'	1.813	6.525	$Fe^{\cdot\cdot\cdot}$	0.1930	0.695
NO_3'	0.642	2.312	$H^{\cdot}$	0.01044	0.03758
O''	0.0829	0.2983	$Hg^{\cdot}$	2.072	7.46
OH'	0.1762	0.634	$K^{\cdot}$	0.4056	1.460
SiO_3''	0.3957	1.425	$Li^{\cdot}$	0.0728	0.2622
S''	0.1661	0.598	$Mg^{\cdot\cdot}$	0.1262	0.4542
Se''	0.4102	1.477	$Mn^{\cdot\cdot}$	0.2849	1.025
SO_4''	0.4975	1.791	$Na^{\cdot}$	0.2388	0.860
Te''	0.661	2.379	$Ni^{\cdot\cdot}$	0.3040	1.094
			$NH_4^{\cdot}$	0.1869	0.673
			$Pb^{\cdot\cdot}$	1.072	3.858
			$Sb^{\cdot\cdot\cdot}$	0.415	1.494
			$Sn^{\cdot\cdot}$	0.616	2.219
			$Sn^{\cdot\cdot\cdot\cdot}$	0.3082	1.109
			$Sr^{\cdot\cdot}$	0.4537	1.633
			$Te^{\cdot\cdot\cdot\cdot}$	0.3305	1.190
			$Tl^{\cdot}$	2.114	7.61
			$Zn^{\cdot\cdot}$	0.3387	1.219

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167. **Electric endosmosis.** Since the above reaction is that of the so-
led diaphragm processes of brine electrolysis, it should be mentioned
e that the introduction of a diaphragm into an electrolytic cell involves
rther complication since it causes the phenomenon of electric endosmosis.
ution is bodily carried through the diaphragm, the amount depending
the nature of the diaphragm. This phenomenon may upset all results
calculation of concentration changes from the transport numbers of ions.
is phenomenon is the reverse of the migration of colloids in solutions
der the action of a current. The colloids correspond to the diaphragm
our former case, but the colloids are movable, while in our former case
diaphragm was fixed. Hence in our former case the liquid will be
placed with respect to the diaphragm. In the latter case the colloids
ve with respect to the stationary liquid.

168. **Short-cut calculations of electrochemical reactions.** It is
ongly recommended to proceed in the way outlined above in making all
culations on electrochemical reactions; since in this way not only all ques-
ns as to details of the reaction are answered, but a clear picture of the
chanism of the reaction is obtained. With ordinary care it is then almost
possible to make a mistake. Nevertheless, for checking results thus
tained or for quick preliminary calculations, tables of electrochemical
uivalents are found useful. We give two of them: Par. **166** referring to the
ctrochemical equivalents of all ordinary ions, Par. **170** to **172** to the elec-
chemical equivalents of the elements.

From Par. **166** one can find immediately by simple addition for most
mpounds of ordinary practice the **quantity of material involved in**
ctrolysis. For instance, for the reaction of sodium chloride electrolysis
a diaphragm cell

$$NaCl + H_2O = NaOH + Cl + H, \qquad (33)$$

find directly from the table that 1 amp-hr. produces 0.03759 g. H and
22 g. Cl. We can further find the quantity of NaCl decomposed per
pere-hour, by adding the figures 0.860 (Na) and 1.322 (Cl), which gives
82 grams NaCl. In the same way the quantity NaOH formed per
pere-hour is found by adding 0.860 (Na) and 0.634 (OH), which gives
94 g. NaOH.

An important precaution which one has to take in the use of this
ble, is to **select** the ion of the **proper valency.** Thus it will be seen
at figures are given for the monovalent $Cu^{\cdot}$ and for the bivalent $Cu^{\cdot\cdot}$ ion.
case of the bivalent compound $CuSO_4$, for instance, one has to select the
ure for $Cu^{\cdot\cdot}$ and finds the quantity of $CuSO_4$, decomposed per hr. = 1.186
1.791 = 2.977 g. (Concerning the necessity of using this table
utiously and judiciously, see also Par. **169.**)

Par. **170** to **172** are tables of electrochemical equivalents of elements and
swers directly the question as to the **quantity of the element adduced**
the anode or reduced at the cathode. Since adduction and reduction
special cases of change of valency, column 4 is headed "change of valency,"
this covers the most general case. In the special case that a metal is de-
sited from a solution or that a gas is evolved at an electrode, it is to be con-
lered that the metal or the gas has no bonds in the free elementary state, so
at in this case the change of valency is equal to the valency in the com-
und. For instance, in the reduction of Cu from CuCl the change of val-
cy is 1, while in the reduction of Cu from $CuSO_4$, it is 2.

In column 4 those changes of valency are given which are most likely to
cur in practice. Thus, for iron, Fe, the figures are given for the changes of
lency 1, 2, 3. In the reduction of a ferric salt to a ferrous salt the change
valency is 1; in the reduction of a ferric salt to metallic iron it is 3; in the
duction of a ferrous salt to metallic iron it is 2. But for every element the
ures are also given for the indefinite change of valency, n, so as to cover
y possible case which may ever arise in practice. To give an example of the
plication of this table, let us assume that in the Bunsen cell nitric acid,
NO_3, is all reduced to nitric oxide, NO, and let us calculate the quantity
nitric acid thus consumed per ampere-hour. Since the valency of N is 5
HNO_3 and 2 in NO, the change of valency of N is 3. From the table we
d directly that for this change of valency 0.174 g. of N are involved in the
duction per ampere-hour. The amount of HNO_3 consumed and of NO
oduced is then found by the ordinary chemical method. The atomic
ight of N is 14, the molecular weight of HNO_3 is $1+14+3\times16=63$, the

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molecular weight of NO is $14+16=30$. Hence $63\times0.174+14=0.78$ g. HNO_3 is reduced and $30\times0.174+14=0.37$ g. NO is produced per ampere-hour. (A similar very elaborate table, but not covering all elements, is given by Carl Hering in *Electrochemical Industry*, Vol. I (1903), p. 170.

169. Example. The Bunsen-cell example in Par. **168** is an instructive example showing the precaution which must be taken in using the table in Par. **168** of the electrochemical equivalents of ions. If it is desired to find the grams of HNO_3 per ampere-hour, involved in the reaction of the Bunsen cells as sketched above, and if one would use directly the figure 0.03759 for H and 2,312 for NO_3 the result would be 2.35 g. HNO_3 which is just three times the correct value found in (**168**). The reason for the mistake is evident if we write down the whole equation of the reaction

$$3Zn+3H_2SO_4+2HNO_3=3ZnSO_4+2NO+4H_2O. \qquad (34)$$

which shows that $2HNO_3$ are involved in the passage of $6\times96,540$ coulombs. If, therefore, anybody makes a mistake by injudicious use of the table, the table should not be blamed.

170. Electrochemical Equivalents of Elements

1 Element	2 Symbol	3 Atomic weight	4 Change of valency	5 Grams per ampere-hour	6 Ampere-hours per gram
Aluminium	Al	27.1	3	0.3369	2.969
			n	$1.011\div n$	$0.990\times n$
Antimony	Sb	120.2	5	0.896	1.115
			3	1.494	0.669
			2	2.241	0.4462
			n	$4.482\div n$	$0.2231\times n$
Argon	A	39.9	n	$1.488\div n$	$0.672\times n$
Arsenic	As	75.0	3	0.932	1.073
			n	$2.797\div n$	$0.358\times n$
Barium	Ba	137.4	2	2.562	0.3903
			n	$5.124\div n$	$0.1952\times n$
Bismuth	Bi	208.0	3	2.586	0.3868
			n	$7.76\div n$	$0.1289\times n$
Boron	B	11.0	3	0.1367	7.31
			n	$0.4102\div n$	$2.438\times n$
Bromine	Br	79.96	1	2.982	0.3354
			n	$2.982\div n$	$0.3354\times n$
Cadmium	Cd	112.4	2	2.096	0.4772
			n	$4.191\div n$	$0.2386\times n$
Caesium	Cs	132.9	1	4.956	0.2018
			n	$4.956\div n$	$0.2018\times n$
Calcium	Ca	40.1	2	0.748	1.338
			n	$1.495\div n$	$0.669\times n$
Carbon	C	12.00	n	$0.4475\div n$	$2.235\times n$
Cerium	Ce	140.25	3	1.743	0.574
			1	5.23	0.1912
			n	$5.23\div n$	$0.1912\times n$
Chlorine	Cl	35.45	1	1.322	0.756
			n	$1.322\div n$	$0.756\times n$

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170. Electrochemical Equivalents of Elements.—(*Continued*)

1 Element	2 Symbol	3 Atomic weight	4 Change of valency	5 Grams per ampere-hour	6 Ampere-hours per gram
Chromium	Cr	52.1	3	0.648	1.544
			n	$1.943 \times n$	$0.515 \times n$
Cobalt	Co	59.0	2	1.100	0.909
			n	$2.200 \times n$	$0.4545 \times n$
Columbium	Cb	94.	2	1.753	0.571
			n	$3.505 \times n$	$0.2853 \times n$
Copper	Cu	63.6	2	1.186	0.843
			1	2.372	0.4216
			n	$2.372 \times n$	$0.4216 \times n$
Erbium	Er	166.	3	2.063	0.4846
			n	$6.19 \times n$	$0.1615 \times n$
Europium	Eu	152.	n	$5.67 \times n$	$0.1764 \times n$
Fluorine	F	19.0	1	0.709	1.411
			n	$0.709 \times n$	$1.411 \times n$
Gadolinium	Gd	156.	n	$5.82 \times n$	$1.719 \times n$
Gallium	Ga	70.0	3	0.870	1.149
			n	$2.610 \times n$	$0.383 \times n$
Germanium	Ge	72.5	4	0.676	1.480
			2	1.352	0.740
			n	$2.704 \times n$	$0.3699 \times n$
Glucinum	Gl	9.1	2	0.1697	5.89
			n	$0.3393 \times n$	$2.947 \times n$
Gold	Au	197.2	3	2.451	0.4080
			2	3.677	0.2720
			1	7.35	0.1360
			n	$7.35 \times n$	$0.1360 \times n$
Helium	He	4.0	n	$0.1492 \times n$	$6.70 \times n$
Hydrogen	H	1.008	1	0.03759	26.60
			n	$0.03759 \times n$	$26.60 \times n$
Indium	In	115.0	3	1.429	0.700
			n	$4.288 \times n$	$0.2332 \times n$
Iodine	I	126.97	1	4.735	0.2112
			n	$4.735 \times n$	$0.2112 \times n$
Iridium	Ir	193.0	3	2.399	0.417
			1	7.20	0.139
			n	$7.20 \times n$	$0.139 \times n$
Iron	Fe	55.9	3	0.695	1.439
			2	1.042	0.959
			1	2.085	0.4797
			n	$2.085 \times n$	$0.4797 \times n$

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170. Electrochemical equivalents of elements.—(*Continued*)

1 Element	2 Symbol	3 Atomic weight	4 Change of valency	5 Grams per ampere-hour	6 Ampere-hours per gram
Potassium	K	39.15	I	1.460	0.685
			n	$1.460 \div n$	$0.685 \times n$
Praseodymium	Pr	140.5	3	1.746	0.573
			n	$5.24 \div n$	$0.1909 \times n$
Radium	Rd	225.0	n	$8.39 \div n$	$0.1192 \times n$
Rhodium	Rh	103.0	2	1.921	0.521
			1	3.841	0.260
			n	$3.841 \div n$	$0.260 \times n$
Rubidium	Rb	85.5	1	3.188	0.3136
			n	$3.188 \div n$	$0.3136 \times n$
Ruthenium	Ru	101.7	4	0.948	1.055
			2	1.896	0.5274
			1	3.792	0.2637
			n	$3.792 \div n$	$0.2637 \times n$
Samarium	Sa	150.3	3	1.868	0.535
			n	$5.61 \div n$	$0.1784 \times n$
Scandium	Sc	44.1	3	0.548	1.824
			n	$1.645 \div n$	$0.608 \times n$
Selenium	Se	79.2	4	0.738	1.354
			2	1.477	0.677
			n	$2.953 \div n$	$0.3386 \times n$
Silicon	Si	28.4	4	0.2648	3.777
			n	$1.059 \div n$	$0.944 \times n$
Silver	Ag	107.93	1	4.025	0.2485
			n	$4.025 \div n$	$0.2485 \times n$
Sodium	Na	23.05	1	0.860	1.163
			n	$0.860 \div n$	$1.163 \times n$
Strontium	Sr	87.6	2	1.633	0.612
			n	$3.267 \div n$	$0.306 \times$
Sulphur	S	32.06	2	0.598	1.673
			1	1.196	0.836
			n	$1.196 \div n$	$0.836 \times n$
Tantalum	Ta	181.0	5	1.350	0.741
			n	$6.75 \div n$	$0.1482 \times n$
Tellurium	Te	127.6	4	1.190	0.841
			2	2.379	0.4203
			n	$4.758 \div n$	$0.2102 \times n$
Terbium	Tb	159.2	3	1.979	0.505
			n	$5.94 \div n$	$0.1684 \times n$

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170. Electrochemical Equivalents of Elements.—*(Concluded)*

1 Element	2 Symbol	3 Atomic weight	4 Change of valency	5 Grams per ampere-hour	6 Ampere-hours per gram
Thallium	Tl	204.1	3	2.537	0.3941
			1	7.61	0.1314
			n	$7.61 \div n$	$0.1314 \times n$
Thorium	Th	232.5	4	2.168	0.4614
			n	$8.67 \div n$	$0.1153 \times n$
Thulium	Tm	171.	n	$6.38 \div n$	$0.1568 \times n$
Tin	Sn	119.0	4	1.109	0.901
			2	2.219	0.4507
			n	$4.438 \div n$	$0.2253 \times n$
Titanium	Ti	48.1	4	0.4484	2.230
			3	0.598	1.673
			1	1.794	0.5575
			n	$1.794 \div n$	$0.5575 \times n$
Tungsten	W	184.0	2	3.431	0.2915
			n	$6.862 \div n$	$0.1457 \times n$
Uranium	U	238.5	6	1.482	0.675
			4	2.223	0.4498
			2	4.447	0.2249
			n	$8.89 \div n$	$0.1124 \times n$
Vanadium	V	51.2	5	0.3819	2.619
			4	0.4773	2.095
			3	0.636	1.571
			2	0.955	1.047
			1	1.909	0.524
			n	$1.909 \div n$	$0.524 \times n$
Xenon	Xe	128.	n	$4.773 \div n$	$0.2095 \times n$
Ytterbium	Yb	173.0	3	2.150	0.465
			n	$6.45 \div n$	$0.1550 \times n$
Yttrium	Yt	89.0	3	1.106	0.9039
			n	$3.319 \div n$	$0.3013 \times n$
Zinc	Zn	65.4	2	1.219	0.820
			n	$2.439 \div n$	$0.4100 \times n$
Zirconium	Zr	90.6	4	0.845	1.184
			n	$3.379 \div n$	$0.2960 \times n$

171. Basis of tables (Par. 170). All the figures in our tables have been calculated on the basis of the atomic weight determinations (table of International Committee for 1907) and on the basis of the value 1.118 mg. per coulomb for the electrochemical equivalent of silver, which value was adopted by the International Electrical Congress in Chicago in 1893. (They have not been recalculated for the changes in the international table of atomic weights since 1907, since the changes would be too small to be of practical importance.)

172. Conversion ratios for electrochemical calculations. To find **milligrams per ampere-second,** divide grams per ampere-hour (column 5) by 3.6.

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To find **ampere-seconds per milligram** multiply ampere-hours per gram column 6) by 3.6.

To find **grams per watt-hour** or **kilograms per kilowatt-hour**, divide rams per ampere-hour (column 5) by volts.

To find **watt-hours per gram** or **kilowatt-hours per kilogram**, ultiply ampere-hours per gram (column 6) by volts.

To find **kilograms per horsepower-hour**, multiply grams per ampere-our (column 5) by 0.74565 (about ¾) and divide by volts.

To find **horsepower-hours per kilogram**, multiply ampere-hours per ram (column 6) by 1.3411 (about 4/3) and by volts.

To find **kilograms per electric horsepower-year**, multiply grams per mpere-hour (column 5) by 6,532 and divide by volts.

THE E.M.F. OF ELECTROLYTIC REACTION

173. E.m.f. and terminal voltage. We have before explained that it is ecessary to distinguish clearly between the voltage at the terminals of an lectrolytic cell, and the e.m.f. of the electrolytic process proper (Par. **140**). We have also shown how to calculate approximately the latter e.m.f. by eans of Thomson's rule from the total energy of reaction, while it should trictly be calculated from the free energy of reaction (Par. **58**). The asiest method to determine the latter, however, is by measurements of otential.

174. Single potentials of elements are determined against normal elec-rodes or standard electrodes. The most usual normal electrodes are the **ydrogen electrode** (platinised platinum, saturated and covered with ydrogen gas, in an acid solution of normal concentration of the hydrogen ons), and the **calomel electrode** (mercury covered with calomel, HgCl, n contact with a normal KCl solution). In order to have a zero point in he potential series of elements, Nernst proposes to make the potential of ydrogen zero. On this supposition the calomel electrode has the potential − .283; in other words if we form a cell of a calomel electrode and a hydrogen lectrode, it has the e.m.f. −0.283, the current in the cell being directed from he latter to the former. On the basis of a theory of Helmholtz on the sur-ace tension of polarised mercury, Ostwald has endeavored to determine 'absolute potentials;" in the absolute series the hydrogen electrode has the bsolute potential −0.277 volt and the calomel electrode the absolute poten-ial −0.560 volt. But this theory is very doubtful.

175. Potential of Various Elements in Order of Their Nobility

	Potential against hydrogen electrode	Absolute potential
Mn	+1.075 volt	+0.798 volt
Zn	+0.770	+0.493
Cd	+0.420	+0.143
Fe	+0.344 (0.660)	+0.067 (+0.383)
Tl	+0.322	+0.045
Co	+0.232 (0.450)	−0.045 (+0.173)
Ni	+0.228 (0.600)	−0.049 (+0.323)
Pb	+0.151 (0.148)	−0.126 (−0.129)
H	±0.0 (by definition)	−0.277
Cu	−0.329	−0.606
Hg	−0.753 (0.750)	−1.030 (−1.027)
Ag	−0.771 (0.798)	−1.048 (−1.075)
Cl	−1.353 (1.400)	−1.630 (−1.677)
Br	−0.993 (1.095)	−1.270 (−1.372)
I	−0.520 (0.628)	−0.797 (−0.905)

176. Order of nobility of elements. The table in Par. **175** gives in the irst column the series of elements in the order of their nobility; those above H are called less noble than H, those below H are called more noble than H. A less noble metal passes into solution when in contact with hydrogen ions, a nore noble metal is not attacked. The second and third columns give the otentials of the elements in a normal solution of one of their salts, for nstance, silver in a silver salt solution. In the second column Nernst's

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zero point of the potential of hydrogen is used; *i.e.*, the figures give directly the potentials of the different elements against the hydrogen electrode. The third column gives the absolute potentials. The figures in the second column are given from H. Danneel and E. S. Merriam's "Electrochemistry;" where Le Blanc, Whitney and Brown in "Handbook of Electrochemistry" (1907) give different values, the latter are added in parenthesis. The voltage of the calomel electrode is 0.283 in the scale of the second column and 0.56 in the third column.

177. The Decomposition Voltage of Various Solutions

(Determined experimentally, chiefly for normal solutions, by Le Blanc and others)

Acids		Potassium hydrate	= 1.67 volts
Sulphuric	= 1.67 volts	Ammonium hydrate	= 1.74 volts
Nitric	= 1.69 volts	0.25 *n* Methylamine	= 1.75 volts
Phosphoric	= 1.70 volts	0.50 *n* Diethylamine	= 1.68 volts
Monochloracetic	= 1.72 volts	0.125 *n* Tetramethylammonium hydrate	= 1.74 volts
Dichloracetic	= 1.66 volts		
Malonic	= 1.69 volts		
Perichloric	= 1.65 volts	**Salts**	
Dextrotartaric	= 1.62 volts	Zinc sulphate	= 2.35 volts
Pyrotartaric	= 1.57 volts	Zinc bromide	= 1.80 volts
Trichloracetic	= 1.51 volts	Nickelous sulphate	= 2.09 volts
Hydrochloric	= 1.31 volts	Nickelous chloride	= 1.85 volts
Hydrazoic	= 1.29 volts	Lead nitrate	= 1.52 volts
Oxalic	= 0.95 volts	Silver nitrate	= 0.70 volts
Hydrobromic	= 0.94 volts	Cadmium nitrate	= 1.98 volts
Hydriodic	= 0.52 volts	Cadmium sulphate	= 2.03 volts
		Cadmium chloride	= 1.88 volts
Bases		Cobaltous sulphate	= 1.92 volts
Sodium hydrate	= 1.69 volts	Cobaltous chloride	= 1.78 volts

178. Overvoltage. In determining the decomposition voltage of a solution which yields gas at an electrode, the peculiar phenomenon is observed that the decomposition voltage depends on the chemical nature of the electrode at which the gas is evolved. Thus hydrogen gas is most easily developed at a platinized platinum electrode while a higher voltage is required at other metals; for instance to evolve hydrogen gas at a zinc electrode, an excess of 0.70 volt is required over the voltage required to evolve hydrogen at a platinized platinum electrode; 0.70 is called the excess voltage or "overvoltage" (überspannung) of hydrogen at a zinc electrode.

179. The Overvoltage of Hydrogen and Oxygen at Different Electrodes

Overvoltage of hydrogen		Overvoltage of oxygen	
Metal	Potential	Metal	Potential
Pt platinized	0.00 volt	Au	1.75 volts
Au	0.01	Pt polished	1.67
Fe in NaOH	0.08	Pd	1.65
Pt polished	0.09	Cd	1.65
Ag	0.15	Ag	1.63
Ni	0.21	Pb	1.53
Cu	0.23	Cu	1.48
Pd	0.46	Fe	1.47
Sn	0.53	Pt platinized	1.47
Pb	0.64	Co	1.36
Zn	0.70	Ni polished	1.35
Hg	0.78	Ni sponge	1.28

180. Thermo-chemical constants. Since Thomson's rule (Par. 83) enables one to find the **e.m.f. of an electrolytic process** from the total energy of the reaction—at least as a first approximation, but with sufficient accuracy for most practical purposes—the tables in Par. **181** to **183**—of voltages calculated from thermochemical data should be found useful. They are reproduced from a paper of J. W. Richards in *Journal* of the Franklin Institute, February and March, 1906. The great convenience in the use of

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hese tables rests in giving the "thermochemical constants" and the cor-esponding voltages separately for the basic elements and the acid elements nd acid radicals. This separation of the two constituents of a salt in solu-on is possible on account of the experimental fact that taking the heats of ormation of salts plus their heat of solution in excess of water (usually called heat of formation to dilute solution"), these quantities are found to be dditive in their nature, such being composed of the sum of two quantities, one haracteristic once for all of the base, in all its combinations, and the other eing characteristic once for all of the acid radical, in all of its combinations. 'here is thus for each basic element a thermochemical constant, which :presents the amount of heat it contributes to the formation-heat of a salt, ie latter taken in dilute solution; and for each acid radical a similar thermo-hemical constant, representing in a similar manner the part which it con-ibutes; the sum of these two thermochemical constants is the formation heat f the salt, from its elements, to dilute solution. The thermochemical con-ant is nothing more nor less, in the case of a base, than energy drop which :presents the decrease of energy in the element as it passes from the free, ncombined state into the dissolved (ionic) state in dilute solution; in the ase of an acid element, the statement is entirely similar; in the case of an cid (or basic) radical, it is the total energy drop from free elements to the onic state as a radical.

The arbitrary basis selected to which to refer these thermochemical onstants is that of hydrogen constant equal to zero. This makes the hermochemical constant of every basic element the heat evolved when it isplaces hydrogen from a dilute solution of acid; and that of an acid ele-ient or radical the heat of formation of the acid in dilute solution.

The "corresponding voltages" given are therefore those which accord-ig to Thomson's rule should be found against a "hydrogen electrode." he figures may therefore be compared with the table in Par. **175** of voltages f various metals against a hydrogen electrode. The difference between ie values of the two tables correspond to the differences in the free energy nd the total energy. For many elements the agreement is quite good. 'hus for Zn the voltage corresponding to the free energy is 0.770, that cor-esponding to the total energy is 0.75.

31. Thermochemical Constants of Basic Elements per Chemical Equivalent and Corresponding e.m.f.

(J. W. RICHARDS)

	Calories	Volts		Calories	Volts
.i	+62,900	+2.73	Cd	9,000	0.36
Rb	62,000	2.69	Co	8,200	0.36
(	61,900	2.69	Ni	7,700	0.33
Ba	59,950	2.60	Fe (ferric)	3,230	0.14
Sr	58,700	2.55	Sn	1,900	0.08
Na	57,200	2.48	Pb	400	0.02
Ca	54,400	2.36	H	0	0
Mg	54,300	2.36	Tl	− 900	−0.04
Al	40,100	1.74	Cu	− 7,900	−0.34
N+H4)	33,400	1.45	Hg	−14,250	−0.62
Mn	24,900	1.08	Pt	−19,450	−0.84
Zn	17,200	0.75	Ag	−25,200	−1.10
Fe (ferrous)	10,900	0.47	Au	−30,300	−1.32

The thermochemical constants in Dr. Richards' table are given in very case for *one* chemical equivalent and not for the number of equiva-nts which are designated by the number of dots (positive bonds) or strokes negative bonds). In using these tables, it must be borne in mind that he sum of the thermochemical constants for the basic and acid constituents f any salts, gives the heat of formation of the salt from the constituent hemical elements, in dilute solution. Conversely, the heat of formation hus obtained is the energy necessary to separate the salt in dilute solu-ion into its constituent chemical elements. The sum of the voltages, orresponding to this amount of chemical energy, is the voltage necessary o decompose the salt in solution into its constituents, free chemical elements. f these elements re-combine in the process of decomposition to form other hemical compounds, then the whole chemical reaction must be taken into

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account, and when this is expressed in calories per chemical equivalent concerned, the necessary voltage for producing the change is obtained by multiplying this by 0.0000434.

182. Thermochemical Constants of Acid Radicals
From their elements (J. W. RICHARDS)

Constituents	Radical	Per chemical equivalent (calories)	Corresponding e.m.f. (volts)	Salts
$O_2(gas)\,H_2(gas)$	$(OH)'$	+55,200	+2.40	Hydrate
$S(solid)\,H_2(gas)$	$(SH)'$	3,400	0.15	Sulphydrate
$Se(met)\,H_2(gas)$	$(SeH)'$	19,100	0.83	Selenhydrate
$Cl_2(gas)\,O_2(gas)$	$(ClO)'$	27,500	1.19	Hypochlorite
$Cl_2(gas)\,O_2(gas)$	$(ClO_2)'$	21,900	0.95	Chlorate
$Cl_2(gas)\,O_2(gas)$	$(ClO_4)'$	39,400	1.71	Per-chlorate
$Br_2(gas)\,O_2(gas)$	$(BrO)'$	28,600	1.24	Hypo-bromite
$Br_2(gas)\,O_2(gas)$	$(BrO_3)'$	12,500	0.54	Bromate
$I(gas)\,O_2(gas)$	$(IO_3)'$	65,000	2.82	Iodate
$I(gas)\,O_2(gas)$	$(IO_4)'$	52,600	2.28	Per-iodate
$S(solid)\,O_2(gas)$	$(S_2O_4)''$	71,750	3.11	Hypo-sulphite
$S(solid)\,O_2(gas)$	$(SO_3)''$	75,100	3.26	Sulphite
$H_2(gas)\;S(solid)\,O_2(gas)$	$(HSO_3)'$	149,400	6.48	Bi-sulphite
$S(solid)\,O_2(gas)$	$(S_2O_5)''$	115,200	5.00	Pyro-sulphite
$S(solid)\,O_2(gas)$	$(SO_4)''$	107,000	4.64	Sulphate
$H_2(gas)\;S(solid)\,O_2(gas)$	$(HSO_4)'$	211,100	9.16	Bi-sulphate
$S(solid)\,O_2(gas)$	$(S_2O_8)''$	158,100	6.86	Per-sulphate
$S(solid)\,O_2(gas)$	$(S_2O_6)''$	138,500	6.01	Di-thionate
$S(solid)\,O_2(gas)$	$(S_3O_6)''$	136,500	5.92	Tri-thionate
$S(solid)\,O_2(gas)$	$(S_4O_6)''$	130,600	5.67	Tetra-thionate
$S(solid)\,O_2(gas)$	$(S_5O_6)''$	133,100	5.78	Penta-thionate
$Se(solid)\,O_2(gas)$	$(SeO_3)''$	60,050	2.61	Selenite
$Se(solid)\,O_2(gas)$	$(SeO_4)''$	72,800	3.16	Selenate
$P(solid)\,O_2(gas)$	$(PO_4)'''$	99,300	4.31	Phosphate
$H_2(gas)\;P(solid)\,O_2(gas)$	$(HPO_4)''$	152,750	6.63	Mono-H-Phosphate
$H_2(gas)\;P(solid)\,O_2(gas)$	$(H_2PO_4)'$	307,700	13.35	Di-H-Phosphate
$As_2(solid)\,O_3(gas)$	$(AsO_2)''$	102,150	4.43	Arsenite
$As(solid)\,O_2(gas)$	$(AsO_4)'''$	70,200	3.05	Arsenate
$H_2(gas)\;As(solid)\,O_2(gas)$	$(HAsO_4)''$	71,700	3.11	Mono-H-Arsenate
$H_2(gas)\;As(solid)\,O_2(gas)$	$(H_2AsO_4)'$	217,200	9.43	Di-H-Arsenate
$N_2(gas)\,O_2(gas)$	$(NO_2)'$	48,800	2.12	Nitrate
$N_2(gas)\,O_3(gas)$	$(NO_3)'$	27,000	1.17	Nitrite
$N_2(gas)\,O_2(gas)$	$(NO)'$	−3,800	−0.16	Hypo-nitrite
$C(amor.)\,O_2(gas)$	$(C_2O_4)''$	99,800	4.33	Oxalate
$C(amor.)\,O_2(gas)$	$(CO_3)''$	82,450	3.58	Carbonate
$H_2(gas)\;C(amor.)\,O_2(gas)$	$(HCO_3)'$	169,100	7.34	Bi-Carbonate
$H_2(gas)\;C(amor.)\,O_2(gas)$	$(CHO_2)''$	104,600	4.54	Formate
$H_2(gas)\;C(amor.)\,O_2(gas)$	$(C_2H_3O_2)''$	120,500	5.23	Acetate
$N_2(gas)\;C(amor.)\,O_2(gas)$	$(CNO)'$	37,100	1.61	Cyanate
$C(amor.)\,N_2(gas)$	$(CN)'$	−34,900	−1.51	Cyanide
$S(solid)\;C(amor.)\,N_2(gas)$	$(CNS)'$	−18,100	−0.79	Sulpho-cyanide
$Fe(solid)\;C(amor.)\,N_2(gas)$	$(FeC_6N_6)'''$	−25,600	−1.11	Ferro-cyanide
$Fe(solid)\;C(amor.)\,N_2(gas)$	$(FeC_6N_6)''$	−52,800	−2.29	Ferri-cyanide

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183. Thermochemical Constants of Acid Elements
(J. W. Richards)

	Per chemical equivalent, calories	Corresponding e.m.f. volts	Salt
F2'' (gas)	+52,900	+2.30	Fluoride
Cl2'' (gas)	39,400	1.71	Chloride
Br'' (gas)	32,300	1.40	Bromide
Br' (liquid)	28,600	1.20	Bromide
Br' (solid)	27,300	1.18	Bromide
I'' (gas)	20,000	0.87	Iodide
I' (liquid)	14,600	0.63	Iodide
I' (solid)	13,200	0.57	Iodide
S'' (solid)	− 5,100	−0.22	Sulphide
Se'' (met.)	−17,900	−0.78	Selenide

INDUSTRIAL ELECTROLYTIC PROCESSES

184. Electroanalysis. As to electroanalysis reference should be had to the book of Edgar F. Smith or to that by A. Classen. The chief reason why electroanalytical methods have found introduction into industrial laboratories is the great ease and the very considerable reduction in time required for an analysis as a consequence of recent improvements mainly due to E. F. Smith and his school. The chief features of these improvements are the use of a rotating anode and of a mercury cathode. The mercury cathode absorbs the metal of the salt solution which is electrolysed. The anode is generally made of such a substance as to absorb the anion. The anode is rapidly dissolved to provide such a circulation of the electrolyte that a high current density may be used with a corresponding reduction in the duration of an analysis. Concerning rapid methods of electroanalysis see the latest edition of Smith's "Electroanalysis."

185. Electrotyping. The object of electrotyping is to reproduce printers' set-up type, engravings, medals, etc. A mould of the object to be reproduced is first made, for instance of wax, by impressing the object in wax. If the mould is a non-conductor of electricity, as in the case of wax, its surface is made conducting by giving it, with a brush, a coating of plumbago (graphite). Instead of a plumbago coating, the mould may receive a metallic coating, for instance of copper as follows: Pour copper sulphate solution over the surface of the mould and dust on it from a pepper-box very finely divided iron filings, brushing the mixture over the surface.) By suitable electrical connections of clamps or wire to the surface of the mould the latter is then made cathode in an electroplating bath, which is made up by preparing an 8 to 10 per cent. solution of sulphuric acid in water and dissolving in it copper sulphate until the resulting solution is saturated at ordinary temperatures. The solution is maintained saturated by adding some crystals of copper sulphate, or by using a copper anode. In the case of reproducing type matter, two cases containing prepared moulds are always suspended back to back between two large copper anodes so that the conducting surfaces of the moulds directly face the anodes. The thickness of the copper deposit depends on the product of current (in amperes) and time; a certain circulation of the electrolyte is useful for the same reasons as in electroplating (see below). The copper shell is then separated from the mould on which it is deposited, and in order to give it the necessary strength for further use it is backed with type-metal.*

ELECTROPLATING

186. General principles of electroplating. The object which is to receive a coating of a metal, is employed as cathode in a solution of a salt of this metal. The anode may either be soluble and consist of the same metal or it may be inert; the object of the former arrangement is to get as much metal dissolved from the anode as is deposited upon the cathode

* Description of a modern electrotyping plant in *Met. & Chem. Eng'ing*, Vol. X, p. 442.

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during the plating process; on the other hand, if an inert anode is used it is necessary to regenerate the solution and add new material in some form to the solution at intervals during operation in order to make up for the metal lost by deposition on the cathode.

In an electroplating bath in which the anode consists of the same metal as that which is plated out on the cathode, the electrochemical reaction at the cathode is the reverse of that at the anode, so that no e.m.f. is required to bring this reaction about (if we neglect the very small e.m.f. required to overcome the concentration differences which establish themselves in the cell). The e.m.f. applied at the terminals of the cell is therefore lost by overcoming the ohmic resistance, and equals current multiplied by internal resistance of the cell. In case an inert anode is used, for instance a platinum anode in a copper sulphate solution for copper plating, oxygen is evolved and sulphuric acid is formed at the anode while the copper is plated out on the cathode. The anodic reaction is therefore not the reverse of the cathodic reaction and a certain e.m.f. is required to bring about the reaction. The voltage applied at the electrodes equals in this case the voltage required to overcome the ohmic resistance of the cell plus the decomposition voltage of the solution. The ohmic loss of voltage should always be made as small as possible, while the decomposition voltage of any solution is also always relatively small, never more than a few volts (see Par. **177**). As a consequence of this it is clear that the voltage at the electrodes of a plating cell must be relatively low: it is in practice generally between a fraction of 1 volt and 6 volts. For this reason **dynamos for electroplating purposes** are low-voltage dynamos. It is, of course, possible and it is quite usual to connect a number of cells in series; in this case the value of the current is the same through all cells in series, while the voltage is the same at the electrodes of the different cells only if the resistance of all cells is the same. In all cases a voltmeter and ammeter should be used by the electroplater so that he always knows exactly the electrical condition of his cells and can regulate them accordingly. Some kind of a rheostat is needed for this purpose.

What the electroplater pays for in paying his electricity bills or in renewing his batteries, is the number of kilowatt-hours consumed. The amount of work performed, *i.e.*, the weight of metal plated out, depends on the other hand, solely on the ampere-hours (for figures see Par. **170**, table of electrochemical equivalents). Hence the old saying that for electroplating (and electrolytic work in general) electrical energy consists of two factors, of which one, the volts, costs money and the other, the ampere-hours, brings money.

187. The only way to reduce the voltage at the electrodes of a plating tank is to reduce the internal resistance. This may be accomplished by increasing the conductivity of the plating bath by suitable additions of high-conductivity electrolytes. It may also be accomplished to a certain extent by placing the anodes very near the articles to be plated. But this should not be overdone, at least when the articles to be plated are in a fixed stationary position, since it is important to get a uniform deposit over the whole surface. For this purpose the density of the electric lines of force should be as uniform as possible over the whole surface, and this condition will be the more fulfilled the further the anode is away from the article to be plated. This precaution is especially necessary when the surface of the article is uneven and irregular and has projecting points.

188. In case a great many small articles are plated simultaneously in one plating tank, the arrangement is generally made to have the articles in continuous motion, so that they tumble over each other and present successively all parts of their surfaces to the electroplating action of the current.

189. Current density at the cathode. The higher the cathodic current density, the greater the total current for an article of given surface and therefore the shorter the time to produce a given weight of deposit on this surface. The output of a plating shop is therefore the greater, the higher the current density. A limit is set to the increase of current density by the fact that by the metal being plated out onto the article under treatment, the solution becomes more and more diluted right at the surface to be plated, and with the decrease of the number of the metal ions at this surface the danger increases that instead of the desired metal something else (for instance

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ydrogen) is plated out. The exact calculation of the decrease of concentration at the cathode resulting from the passage of a certain number of ampere-hours, for copper-plating with copper anodes and a sulphate solution was given before in the discussion of Hittorf's transport numbers. In any case, the higher the current density the quicker is the loss from the solution at the cathode of the metal ions to be plated out and the smaller is the chance for diffusion and convection currents to bring fresh concentrated solution to the cathode surface where it is needed. The higher the current density, the greater is, therefore, the importance of artificial circulation or stirring; for this purpose either one or both electrodes may be revolved or a special stirring device may be employed in the solution. It seems, for instance, that with a smooth copper, zinc or nickel cathode, a good copper, zinc or nickel deposit can be obtained, however high the current density may be raised, if only the cathode is revolved at an increasing and sufficiently high speed. Heating also aids circulation.

190. Junction between the metals. In contradistinction to electrotyping it is very important in electroplating to get a deposit which will stick to the metal on which it is plated. There must be an intimate junction between the two metals and, according to L. Kahlenberg (*Electrochemical Industry*, Vol. I, p. 201), this requires that the two metals form an alloy together. Thus nickel may be successfully plated on copper and its alloys (brass, bronze, etc.), since with these nickel alloys readily. On the other hand, if an object of lead is to be nickeled, it is first copper plated and then the nickel is deposited on the copper because copper alloys better with lead than does nickel.

191. In order to make the deposit stick to the metal underneath, it is also of fundamental importance that the surface metal before being plated is carefully cleaned both mechanically and chemically, and that all traces of fat and oil, etc., are thoroughly removed. To remove grease, a caustic soda solution or a caustic potash solution is suitable, the latter being preferable. Acid solutions for cleaning gold, silver, copper, brass and zinc surfaces are being recommended by Trevert as follows:

	Copper	Zinc	Silver	Iron
Water	100	100	100	100
Nitric acid	50	—	10	2 to 3
Sulphuric acid	100	10	—	8 to 12
Hydrochloric acid	2	—	—	2 to 3

192. The plating bath contains principally the salt of the metal which is to be plated out, together with the addition of a solution of high conductivity, so as to reduce the voltage drop. However, other additions have also been found useful, for the following reasons: At moderate current densities a bad deposit is practically always due to the precipitation of a non-metallic solid with the metal, especially of an oxide, hydroxide or basic salt of the metal. Whatever will dissolve the oxide, etc., readily under the conditions of the operation will prevent its deposition and should therefore improve the quality of the deposit. W. D. Bancroft ("Transactions International Electrical Congress," St. Louis, Vol. II, p. 27, and *Transactions* American Electrochemical Society, Vol. VI) shows that a large majority of the more important additions recommended for various plating baths act in the way just described.

193. Securing fine-grained deposits. It seems that a fine-grained deposit is favored by high-current density and potential difference, by acidity and alkalinity and by low temperatures. Solutions containing oxidizing agents appear to yield small crystals while larger crystals are obtained from solutions containing reducing agents.

194. To prevent the formation of "trees" a very small addition of a colloid has been found useful in several cases. In the deposition of lead from a solution of lead-fluosilicate, containing an excess of hydrofluoric acid, A. G. Betts found that the formation of trees and the deposition of spongy lead could be completely avoided and the deposition of perfectly solid and dense lead could be assured by the simple addition of a very small amount of gelatine or glue added to the bath. Similar observations have been made with silver and copper. The general rule seems to be that

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the addition of a very small amount of such a colloid, which, under the action of the current, migrates toward the cathode, improves the uniformity and density of the deposit.*

195. Practical rules for electroplating. A tentative and very useful theory of the chemical principles which underlie electroplating has been given in the paper by W. D. Bancroft quoted above. Other suggestive hypotheses have been presented by A. G. Betts.† Bancroft has given the following "axioms of electroplating:" (*a*) Bad deposits are due to excessive admixture of some compound or to excessively large crystals; (*b*) excessive admixture of any compound can be eliminated by changing the conditions so that the compound cannot precipitate; (*c*) increasing the current density, increasing the potential difference at the cathode, or lowering the temperature, decreases the size of the crystals; (*d*) the crystal size is decreased when there are present at the cathode surface, substances which are absorbed by the deposited metal; (*e*) if a given solution will give a good deposit at any current density, it will give a good deposit at any higher current density, provided the conditions at the cathode surface are kept constant; (*f*) treeing is facilitated by a high potential drop through the solution and by conditions favorable to the formation of large crystals.

196. For detailed prescriptions of solutions,‡ etc., the reader must be referred to special handbooks for electroplaters, like Watt's and Philip's "Electroplating and Electrorefining of Metals," or the smaller books of van Horne and others. In the following a brief account only is given of some solutions in most common use.

197. Nickel plating.§ The nickel salt, generally used for nickel plating, is nickel ammonium sulphate. For small baths the salt is dissolved by boiling 12 to 14 oz. of the salt per gallon of water in a new stone jar and filling up the bath with water until a hydrometer placed in it stands at 6.5 deg. to 7 deg. Beaumé. The solution should be slightly acid, but too much acid will cause peeling and too much alkali will darken the tone of the work according to van Horne. He recommends the following current density. For plating zinc with nickel, use 0.05 to 0.10 amp. per sq. in. of the surface of the object to be plated; for plating nickel on other metals use half this current density. To improve the quality of the nickel deposit, certain additions to the bath have been recommended. J. Powell recommends the addition of 0.125 oz. of benzoic acid per gallon of solution. E. Weston recommends a solution containing 10 parts nickel ammonium sulphate, 2.5 to 5 parts of boracic acid and 150 to 200 parts of water. Boracic acid is now much employed as an addition. According to F. Foerster, a good deposit of nickel is obtained from its sulphate solution, containing some slight amount of free citric acid or boracic acid, with a current density of 0.005 amp. per sq. cm. A very suitable nickel bath is obtained by dissolving 50 g. of nickel sulphate crystals so as to get one-half liter solution; 20 g. citric acid are then dissolved in water and neutralised by means of caustic soda to such a degree that blue litmus paper is just colored red, and the solution is then diluted to get one-half liter; this is then added to the nickel sulphate solution; this bath requires about 3 volts. There is no danger that the nickel deposit will peel off, as long as the thickness of the deposit thus produced is below 0.01 mm. Thicker deposits may be obtained from neutral or slightly acid nickel sulphate solutions, heated to 70 or 90 deg. cent. (F. Foerster, *Zeit. f. Elektrochemie*. Vol. IV, p. 160). If a more concentrated solution is used (containing 150 to 350 g. of nickel sulphate per liter and preferably also some sodium sulphate) the current

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* *Electrochem. & Met. Ind.*, Vol. IV, p. 379 and 416; see also the papers by Kern and Tucker on the effect of addition agents, Vol. VII, p. 271 and 273.

† *Transact.* Am. Electrochem. Soc., Vol. VIII, p. 63.

‡ An excellent set of papers summarizing all the different solutions proposed and used for plating with gold, silver, cobalt, nickel, lead, tin, copper, brass and bronze may be found in Vol. XXIII of the *Transact.* Am. Electrochem. Soc.

§ A very extended summary of all solutions proposed and used for electroplating with nickel and cobalt is given in a paper by O. P. Watts in *Transact.* Am. Electrochem. Soc., Vol. XXIII, p. 99.

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sity may be raised to 0.02 to 0.08 amp. per sq. cm. and with moderate ulation of the electrolyte good deposits 1 mm. thick may be obtained.

98. Difficulties in nickel plating. A difficulty in nickel plating was nerly found in the fact that the nickel anodes do not dissolve freely in nickel-ammonium sulphate solution. Cast nickel anodes are said to olve better than rolled nickel anodes. For the same reason it is im-tant to use as large a surface of nickel anodes as possible. This has led he introduction of corrugated anodes, etc., and it has been recommended make the nickel anode surface ½ times the surface to be plated. W. Bancroft has recently suggested (*Transactions* American Electrochemical iety, Vol. IX, p. 217) that the greater effectiveness of the cast nickel des is due to the fact that they contain iron. For this reason they will olve better, but iron will also pass into solution, which is a disadvantage. recommends the use of a pure nickel anode in a nickel-ammonium sulphate ution containing a slight percentage of ammonium chloride or nickel chlo-. If this addition is made, the nickel will dissolve as quickly from the de as it is plated out on the cathode. If iron is to be nickeled it should t receive a coating of copper.

99. Silver plating.* The standard solution for silver plating is the uble cyanide of silver and potassium, with silver anodes. As to working a large scale and the production of the silver cyanide from silver nitrate d potassium cyanide and the production of the double cyanide from silver anide and potassium cyanide the reader must be referred to special text-oks. A good silver plating solution is obtained by dissolving 25 g. re silver cyanide in a solution of 25 g. potassium cyanide in 300 to) cu. cm. water and diluting the solution so as to form 1 liter. The best rrent density is 0.001 to 0.0045 amp. per sq. cm., with about 1 volt the terminals of the cell. Another prescription for experimental work is dissolve 3 oz. of silver chloride (rubbed to a thin paste with water) in olution of 9 to 12 oz. of 98 per cent. potassium cyanide in a gallon of ter. A current density of $\frac{1}{10}$ amp. per sq. in. is recommended in the ter case.

100. Gold plating.† The standard solution is the double cyanide of ld and potassium and the problems involved in gold plating are similar many respects to those of silver plating. In view of the expensive ma-ial involved, great care is necessary in details and the reader must be ferred to special books on the subject. Gold is generally plated on cop-r; other metals to be coated with gold first receive a coating of copper; e also (**207**).

101. Copper plating.‡ A copper sulphate solution, containing free id, such as is used for electrolytic refining of copper, may be used for pper plating (see **208**), but better results are obtained with a cyanide lution. van Horne gives the following formula: to each gallon of water ld 5 oz. copper carbonate, 2 oz. potassium carbonate and 10 oz. chem-ally pure potassium cyanide. Dissolve about nine-tenths of the cyanide potassium in a portion of the water and add nearly all of the copper rbonate, previously suspended in a portion of the water; then add the otassium carbonate, also dissolved in water, slowly stirring until thoroughly ixed. Bring the solution to 160 deg. Beaumé, put in a small article and at the solution, adding cyanide or copper or both, until the solution deposits eely and uniformly.

F. Foerster recommends for copper plating a solution made as follows:) g. copper acetate are dissolved in 500 cu. cm. water, 20 g. potassium cya-ide, 25 g. sodium sulphite crystals and 17 g. sodium carbonate crystals are dis-olved in another 500 cu. cm. water. The first solution is then added to ne second one and a current density of 0.003 amp. per sq. cm. is used with volts at the terminals of the cell.

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* A voluminous summary of all recipes for electroplating silver on metals given in a paper by F. C. Frary, *Transact.* Am. Electrochem. Soc., ol. XXIII, p. 25.

† All recipes for gold plating are collected in the paper by F. C. Frary, *Transact.* Am. Electrochem. Soc., Vol. XXIII, p. 25.

‡ A summary and classification of the different solutions for copper plating given in a paper by C. W. Bennett, *Transact.* Am. Electrochem. Soc., Vol. XXIII, p. 233.

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203. Brass solutions* of any desired color are made according to van Horne by adding zinc carbonate in varying proportions to the copper solution. This is done by dissolving about one part by weight of carbonate of zinc to two parts of cyanide of potassium in sufficient water to dissolve them and adding them slowly to the copper bath.

203. Zinc plating. The protection of iron surfaces against rusting by means of a zinc coating is now becoming an important industry. Zinc-coated iron is often called "galvanised" iron. Most processes used in the United States use soluble zinc anodes, while Cowper-Coles in England uses insoluble (lead) anodes in an electrolyte containing 35 oz. of zinc sulphate ($ZnSO_4.7H_2O$) and 0.1 oz. sulphuric acid (specific gravity 1.84) per gallon of water.

A suitable zinc plating solution is obtained, according to Foerster, by dissolving 200 g. pure zinc sulphate (free from iron), 40 g. glauber salt, 10 g. zinc chloride and 0.5 g. boracic acid so as to get 1 liter solution; with a current density of 0.005 to 0.02 amp. per sq. cm. good dense deposits up to 0.05 mm. thickness are thereby obtained at temperatures between 18 and 50° C. The method of producing the zinc coating by electrolysis ("cold galvanising") has the following advantages over the old dipping process ("hot galvanising"); electrolytic zinc, when properly applied, is denser, tougher, more uniform and more resistant against corrosion† (C. F. Burgess, *Electrochemical and Metallurgical Industry*, Vol. III, p. 17).

204. Plating upon aluminium. As an example of the great importance of thoroughly cleaning a surface preliminary to plating upon it, the difficulties of plating upon aluminium may be cited. A coating on aluminium will not stick in general for any length of time and this trouble is due to the invisible film (oxide or hydroxide film) which is always present on an aluminium surface in contact with air, and which prevents the necessary intimate junction between the aluminium and the plated metal. C. F. Burgess and C. Hambuechen (*Electrochemical Industry*, Vol. II, p. 83) found that this film can best be eliminated by using a soluble fluoride in the plating bath; further that of all metals zinc will adhere best to aluminium. Therefore, aluminium should first receive a zinc coating. If the object is to plate gold on the article, the gold should not be plated directly on the zinc since the gold will soon alloy with the zinc and apparently disappear; for this reason the zinc should first receive a copper coating and then the gold coating.

The mode of operation recommended is to first clean the aluminium by immersion for a few minutes in a dilute hydrofluoric acid bath where it remains long enough to produce a suitable roughening of the surface. It is then rinsed in running water and dipped for a few seconds in a mixture of 100 parts of sulphuric acid and 75 parts of nitric acid, both concentrated, from which, after rinsing in water, the aluminium comes perfectly white and clean. The article is then transferred to the zinc plating solution, which is a mixture of zinc and aluminium sulphates, very slightly acidified and having a density of about 15 deg. Beaumé and containing about 1 per cent. of hydrofluoric acid or an equivalent amount of potassium fluoride. After the deposition has proceeded for about 10 or 15 min. with a current density of from 10 to 20 amp. per sq. ft., the article may be taken from the solution and dried. It may then be given a coating of copper or silver from their cyanide solutions, using such precautions as are commonly observed in the deposition of such metals upon zinc. Where the final coating is to be of gold, it is advantageous to polish the copper coating before depositing the gold, as otherwise a thicker gold coating will be necessary to produce the final polish.

205. Detinning.‡ The reverse of electroplating is the electric removal

* A summary of the solutions for brass and bronze plating is given in a paper by C. W. Bennet, *Transact.* Am. Electrochem. Soc., Vol. XXIII, p. 251.

† As to electrolytic zinc plating (cold galvanising) in comparison with hot galvanising and sherardising see Burgess, *Electrochem. & Met. Ind.*, Vol. III, p. 17; Cowper-Coles, Vol. III, p. 189; Storey, *Met. & Chem. Eng'ing*, Vol. XI, p. 190.

‡ K. and H. Goldschmidt. *Electrochem & Met. Ind.*, Vol. VII, p. 79; see also *Met. & Chem. Eng'ing*, Vol. X, p. 202.

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f a metallic coating from the surface of an article. This is generally arried out as an anodic reaction. The most important industry in this eld is the detinning of tin scrap, which has assumed quite considerable imensions in recent years as a consequence of the enormous growth of the n-can industry. While formerly only the tin scrap of the tin-can fac-ories (a pure material, consisting of sheet iron, covered with tin) was reated, the treatment of tin cans, tin boxes, etc., which have been in use, as recently been taken up on a commercial scale; since they contain many npurities, these must first be very thoroughly removed (carbonized, etc.). The object of the electrolytic process is to remove the tin from the iron o as to get both the tin and iron separate and pure. The iron is sold as crap to open-hearth steel works, etc., and must therefore be absolutely ree from tin and in good condition. The process which has been most uccessful on a very large scale is that of the firm of Theodor Goldschmidt in ssen; it is a secret process and employs the scrap as anode in a solution f caustic soda. Since 1906 detinning with chlorine has entered into com-etition with electrolytic detinning. Detinning with chlorine may be con-idered as an electrolytic process only in so far as electrolytic chlorine (see 39) is used. While the products of electrolytic detinning are tin and iron, hose of chlorine detinning are tin tetrachloride and iron. (Karl Gold-chmidt, *Electrochem. & Met. Ind.*, Vol. VII, p. 79.)

206. Other stripping processes. A comparatively small, but inter-sting application of electrolytic stripping is the process of C. F. Burgess or removing from bicycle frames the films of brass which are left there rom brazing the joints. A sodium nitrate solution is used for this purpose. For this and similar processes see C. F. Burgess, *Electrochemical Industry*, 'ol. II, p. 8.) As an example of the cathodic removal of a surface coating, he process of C. J. Reed for removing an oxide scale from iron and steel nay be mentioned. The iron sheets, rods or wire are treated as cathode n a 27 per cent. solution of sulphuric acid of specific gravity 1.20, with a urrent density of 0.25 to 0.5 amp. per sq. in. at a temperature of 60° C. Inder these conditions the heavy scale on rolled iron rods is removed in rom 2 to 3 min. The iron oxide is not reduced to metallic iron, but o a lower state of oxidation and is then dissolved, ferrous sulphate being roduced. (*Transactions* American Electrochemical Society, Vol. XI.) Concerning the sharpening of tools by electrolytic etching see Schneckenberg, *Met. & Chem. Eng'ing*, Vol. IX, p 512.

ELECTROLYTIC REFINING OF METALS

207. Fundamental principles. In electrolytic refining of metals the tarting material is a highly concentrated alloy and the purpose is to remove he last impurities and to recover not only the principal metal in pure form, ut also the foreign metals, especially the precious metals. The impure etal is made the anode and the fundamental principle of the process is hat by the electrolytic action the metal to be refined is dissolved from the node, passes into the electrolyte and is deposited from the electrolyte on the athode in pure form; the foreign metals (impurities) are intended either o remain back in the anode or anode slime without being dissolved, or if hey are dissolved in the electrolyte, they are intended to remain in the lectrolyte without being deposited on the cathode. This cannot be satis-actorily accomplished, except with a comparatively pure, high-grade node; in American practice of copper refining the impure copper anode s generally 98 to 99.5 per cent. pure. The cost of the electrolytic-re-ning process is covered first by the higher price of the refined metal and econdly by the value of the foreign metals recovered, especially silver and old.

208. Copper refining. The electrolyte is a copper sulphate solution ontaining free sulphuric acid. The copper should not exceed 3 per cent. t the most, or 12 per cent. if figured as bluestone. The acid may ad-antageously be run up to about 13 per cent.* (Usually a very small mount of a soluble chloride, like NaCl, is added to precipitate as chloride

* Figures of the conductivity of mixtures of copper sulphate and sulphuric cid are given by Richardson and Taylor in *Trans.* Amer. Electrochem. Soc., 'ol. XX, p. 179.

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any silver which may dissolve and to slime antimony as oxychloride.) An anode of typical composition contains 98 to 99.5 per cent. copper, up to 300 oz. silver per ton, up to 49 oz. gold per ton and up to 2 per cent. arsenic. The cathode copper is exceedingly pure, usually running about 99.93 per cent. copper, with hydrogen as the chief impurity. In order to have high electric conductivity, the copper must be free from arsenic and antimony (the amount should be but a few thousandths of a per cent.); in order to prevent brittleness, the cathode copper must be free from tellurium and lead. Since the electric conductivity of copper very delicately indicates its purity, it is used for giving the figure of the purity. Matthiessen's standard—according to which the resistance of one meter-gram of pure soft copper at 0 deg. cent. is 0.14172 international ohm—is generally used although it is some 3 per cent. too low. It is a "fact that the conductivity of the [electrolytic] copper on the market to-day often exceeds by as much as 1 per cent. the purest laboratory copper of forty years ago." (L. Addicks.)

It is customary to circulate the electrolyte from tank to tank and this is more important the higher the current density. The current density varies in American refineries between 12 and 35 amp. per sq. ft.; the question of what current density to carry is largely one of energy cost. An elevated temperature of the electrolyte is used. Soluble sulphates of impurities in the anode pass into the solution which therefore needs purification at intervals. This is usually done by working up a certain quantity of electrolyte regularly into bluestone and adding fresh acid to the electrolyte.

209. Arrangement of electrodes in copper refining. With respect to the arrangement of the electrodes two different systems are in use. In the parallel system or multiple system all cathodes are in parallel and all anodes are in parallel; the arrangement is shown in Fig. 5. In the series system or Hayden system, diagrammatically shown in Fig. 6, only the first

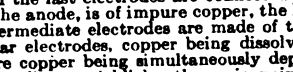


FIG. 5.—Multiple System.

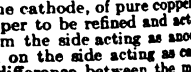


FIG. 6.—Series System.

and the last electrodes are connected to the electric circuit; the first, which is the anode, is of impure copper, the last, the cathode, of pure copper. All intermediate electrodes are made of the copper to be refined and act as bipolar electrodes, copper being dissolved from the side acting as anode and pure copper being simultaneously deposited on the side acting as cathode. According to Addicks, the main points of difference between the multiple system and the series are in energy cost, compactness and cost of preparing anodes. The power in the series system is about 70 per cent. of that in the multiple system. In the multiple tank close attention must be paid to the contacts (B. Magnus, *Electrochemical Industry*, Vol. I, p. 561, Vol. II, p. 74; C. T. Hutchinson, Vol. II, p. 13). The series tank has relatively few contacts or conducting bars, and the electrodes are very close together, the anodes being thin, even plates. To produce such anodes they must either be rolled or specially hand-cast, and the grade of material used must be good. The interest on the metal tied up in process and the investment in plant is less in the series system. The series system requires no starting sheets, but much closer supervision to keep the quality of the cathodes up. As lead-lined tanks cannot be used in series work, due to the relatively high voltages used, tank maintenance becomes an important item.

210. Statistics of copper refining. According to T. Ulke (*Electrochemical Industry*, Vol. I, pp. 240 and 276) the yearly output of American electrolytic copper refineries in 1902 was 279,000 tons. At the same time the amount of silver and gold recovered per year in the copper refineries was 27,000,000 oz. of silver and 346,020 oz. of gold. The capacity of American electrolytic copper refineries in 1918 was 1,500,000 tons, the output 1,200,000 tons.

211. References to literature on copper refining. A very good and concise summary of modern copper refining methods is the article by L. Addicks, *Electrochemical and Metallurgical Industry*, Vol. IV, p. 15.

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e also the monograph of T. Ulke on modern electrolytic copper refining. oncerning treatment of the slimes of copper refineries see below under ver refining, also Kern, *Met. & Chem. Eng'ing*, Vol. IX, p. 417. A full scription of the Great Falls refinery is given by Burns in *Bulletin* American st. Min. Engrs., August, 1913, p. 2011. Concerning the power problem electrolytic copper refining see papers by Addicks, Longwell, and Newbury, ransact. Amer. Electrochem. Soc., Vol. XXV.

212. Silver refining. The chief commercial problem of silver refining lates to the treatment of the bullion produced by copper refineries, to cover the silver and gold. his bullion may be treated ther with the old sulphuric id parting process or electrotically by one of the following methods (for a critical comarison see F. D. Easterbrooks, *ransactions* American Electrochemical Society, Vol. III, p. 125). In the electrotic methods the electrolyte is silver nitrate solution.*

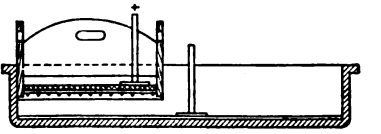


FIG. 7.—Balbach Cell.

213. Balbach process. The cross-section of a tank is shown in Fig. The cathode is made of ½-in. Acheson graphite slabs fitted to the ottom. Two silver contact pieces rest respectively on the bullion to be arted and the graphite slabs. Bullion cast in thin square slabs is contained a cloth case which is supported on a wooden frame suspended over the ank. The gold slimes accumulate on the under side of the bullion, between and the cathode, increasing the resistance as the operation continues. ach tank has a cathode surface of 8 sq. ft., and a current density f 20 to 25 amp. per sq. ft. is used. The voltage averages 3.8 per tank, and n average ampere-hour efficiency of 93 per cent. is obtained on a continued un, while occasionally an efficiency of 98 per cent. is secured. The energy equired is 31.5 watt-hr. per oz. of fine silver produced. At 20 amp. er sq. ft. about 32 per cent. of the daily output of each tank is held permanently in stock in electrolyte and contacts. (For a description of the Balbach refinery see *Electrochemical Industry*, Vol. II, p. 302.) Thum's modification of the Balbach process, as employed on the Raritan Copper Works, is described by Easterbrooks in *Electrochem. & Met. Ind.*, Vol. VI, p. 277.

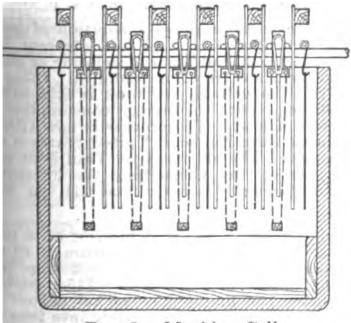


FIG. 8.—Moebius Cell.

214. Moebius process. The cross-section of a tank is shown in Fig. 8. They are arranged in units of 6 placed end to end, each unit being provided with apparatus for raising the boxes containing the deposited silver together with the anodes and cathodes, and with arrangements for imparting a reciprocating motion to the wooden crapers. There is no system of circulating the electrolyte, but the scrapers noving back and forth agitate it. The anodes are contained in a cloth rame which holds the gold slimes, and the silver is brushed off from the ilver cathodes by the wooden scrapers, and drops into a box with hinged ottom. It is removed by raising the boxes above the top of the tanks nd emptying them into a tray placed beneath. This operation requires ½ r. per day per unit. Each tank has a cathode surface of about 16.5 sq. t., and a current density of 20 to 25 amp. per sq. ft. is used. The voltage

* See also Kern, *Met. & Chem. Eng'ing*, Vol. IX, p. 443.

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between electrodes is 1.4 to 1.5 and the energy consumption is 13.2 watt-hr. per os. of silver deposited. A mean ampere-hour efficiency of 94 per cent. is obtained. At 20 amp. per sq. ft. 41 per cent. of the daily output of each unit is permanently in stock in cathodes and electrolyte.

In both the Balbach and the Moebius processes which are in use at various copper refineries the silver is deposited in a loose crystalline form at a relatively high current density. With a lower current density (10 amp. per sq. ft.) silver is deposited in adherent form from a copper-silver nitrate solution, with a small addition of gelatine, with rapid circulation of the solution. The energy consumption is nearly identical with the Moebius method. 28 to 32 per cent. of the daily output is required in cathodes and electrolyte. A. G. Betts (*Transactions* American Electrochemical Society, Vol. VIII, p. 121) recommends an electrolyte of methyl sulphuric acid with a small addition of carbon bisulphide.

215. Treatment of bullion at United States mints. The bullion to be **parted and refined** is divided into two classes, by selection and blending. One class is largely gold (see below gold refining). The other class contains largely silver; the anodes are composed of 300 parts of gold in 1,000, the remaining 700 parts consisting of silver, copper and other material. The electrolyte consists of a 3 per cent. solution of silver nitrate to which is added 1.5 per cent. free nitric acid. The silver deposit is obtained in coherent form if a very small amount of gelatine is added to the electrolyte (D. K. Tuttle, *Electrochemical and Metallurgical Industry*, Vol. IV, p. 306).

216. Gold refining. The **Wohlwill process** of gold refining with recovery of platinum and palladium employs a gold chloride solution strongly impregnated with hydrochloric acid, at a temperature of 65 to 70 deg. cent. A slight modification of the Wohlwill process (55 deg. cent, purer anodes and lower current density) is in use in the United States mints. See E. Wohlwill, *Electrochemical Industry*, Vol. II, pp. 221 and 261, Vol. VI, p. 42; D. K. Tuttle, *Electrochemical Industry*, Vol. I, p. 157; also Vol. VI, pp. 355 and 408. The applicability of the Wohlwill process to alloys rich in silver has been rendered possible recently by the employment of a pulsating current (obtained by superposing an alternating current on the direct current) instead of a purely direct current. (*Met. & Chem. Eng'ing*, Vol. VIII, p. 82). See also Kern, *Met. & Chem. Eng'ing*, Vol. IX, p. 446.

217. Lead refining. The **Betts process** employs a solution of lead fluosilicate, containing an excess of hydrofluoric acid (5 to 7 per cent. H and 12 to 15 per cent. HF) with a very small addition of gelatine or glue depositing lead in dense coherent form and free from bismuth. (*Electrochemical Industry*, Vol. I, p. 407.) The voltage per tank is 0.35 to 0.4 including losses, the temperature 30 deg. cent., the energy consumption is from 5½ to 6 horsepower-days per ton of lead. The process is now (1907) used commercially in three plants in Canada, England, United States of an aggregate capacity of 175 tons per day. The efficiency at Trail is 88 per cent. the current density 15 amp. per sq. ft. Concerning the treatment of slimes see *Electrochemical & Metallurgical Industry*, Vol. III, pp. 141 and 235.

218. Nickel refining. For nickel refining either a chloride or a sulphate solution is used. F. Foerster recommends a temperature of 60 to 70 deg. cent., good circulation and a current density of 0.01 to 0.02 amp. per sq. cm., with a solution containing about 30 g. nickel (=145 g. $NiSO_4$, $7H_2O$ or 121 g. $NiCl_2$, $6H_2O$) or more per liter. The nickel deposit is of such density and tenacity that it may be rolled immediately into form of sheets. Concerning the possibility of obtaining thick coherent nickel deposits see W. McA. Johnson, *Electrochemical Industry*, Vol. I, p. 212; and D. H. Browne, *Electrochemical Industry*, Vol. I, p. 348. Browne obtained good coherent deposits from a neutral solution containing 70 g. $NiCl_2$, 180 NaCl per liter, heated to 50 to 75 deg. cent., with a current density of 100 to 200 amp. per sq. m. with efficient circulation of electrolyte. From sulphate solutions thick cathodes may be deposited, with a solution of neutral nickel-sulphate or nickel-ammonium sulphate, kept at about 50 deg. cent. with efficient circulation and a current density of 50 to 300 amp. per sq. m.

219. Zinc refining. In the **Hoepfner process** which is in use in a plant in England, a zinc chloride solution is subjected to electrolysis. De-

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ils of electrolysis as carried out in England are not known; see, however, . Guenther's "Darstellung des Zinks auf Elektrolytischem Wege." The test advance of the Siemens & Halske Co. in this field is the use of anganese peroxide anodes. The power consumption is 3.4 kw-hr. per ilogram Zn.

220. Iron refining. The **Burgess process** employs a solution of fer- us and ammonium sulphates with a cathodic current density of 6 to 10 np. per sq. ft. and a slightly smaller anodic current density. The e.m.f. r each cell is slightly under 1 volt; the temperature of the electrolyte is out 30 deg. cent.; the anodes consist of ordinary grades of wrought iron and eel; the starting sheets for the cathode are of thin sheet-iron, previously eaned of rust (*Electrochemical Industry*, Vol. II, p. 183). See also E. F. ern, *Transactions* Am. Electrochem. Soc., Vol. XIII.

As an electrolytic iron-refining process and as a plating operation may be nsidered the process of Cowper-Coles† for the production of iron sheets and ibes of nearly pure iron from anodes of pig iron. The electrolyte is a con- ntrated solution of ferrous chloride with addition agents.

221. Tin refining. According to the **Claus process** raw tin is electro- ted in a 10 per cent. sodium sulphide solution at a temperature of more an 80 deg. cent. with a current density of 0.5 amp. per sq. dm. at a voltage the electrodes below 0.2 volt. Pure tin plates or plates coated with pure n must be used as cathodes. (O. Steiner, *Electrochemical and Metallurgical ndustry*, Vol. V, p. 309.) A recently constructed plant at Perth Amboy, . J., refines impure Bolivian tin using a solution of tin fluosilicate with ee HF, similar to the Betts refining bath for lead. (*Mineral Industry*, 917, p. 692.)

222. Bismuth refining. The electrolyte is bismuth chloride contain- g free hydrochloric acid (7 per cent. Bi and 9 to 10 per cent. HCl). The thodic current density is 20 amp. per sq. ft., the anodic current density three times this amount, the voltage at the electrodes is 1.2. Silver d gold remain at the anode, but traces of the silver pass into the bismuth posit. The anodes contain over 90 per cent. Bi, besides lead, silver, c. The product is 99.8 per cent. pure, the chief impurity being silver. ie arrangement of the cell is the same as in the Balbach silver-refining ocess. (A. Mohn, *Electrochemical and Metallurgical Industry*, Vol. V, 314.)

223. Cadmium refining. A cadmium sulphate solution containing e acid is electrolysed with a current density of 0.005 to 0.02 amp. per . cm. (F. Mylius and R. Funk, *Zeit, f. Anorgan. Chemie*, Vol. 13, p. 157.)

224. Miscellaneous refining processes. Cobalt is stated to be de- sited from its sulphate and chloride solutions with the same ease and der the same conditions as nickel. Concerning **thallium** see F. Foerster 'eit, *f. Anorg. Chemie*," Vol. 15, p. 71. Concerning **chromium** see M. Blanc's "Production of Chromium," (English translation by J. W. Rich- ds), also Carveth and Mott, and Carveth and Curry, *Jour. Physical emistry*, Vol. IX, pp. 231 and 353, Le Blanc, *Transactions* of the nerican Electrochemical Society, Vol. IX, p. 315.

ODUCTION OF HYDROGEN AND OXYGEN GASES BY ELEC- TROLYSIS OF WATER

225. General theory. In the electrolytic decomposition of water, as car- d out on an industrial scale for the production of oxygen and hydrogen es, instead of pure water which has too low an electric conductivity, either 0 per cent. solution of sulphuric acid or a 15 per cent. solution of caustic la is used as electrolyte, these concentrations corresponding to maximum nductivity. If sulphuric acid is used, the cathodic reaction is the dicharge hydrogen ions and the setting free of hydrogen gas, while the anodic reac- n may be written

$$SO_4'' + H_2O = H_2SO_4 + O, \qquad (35)$$

that oxygen gas is set free and sulphuric acid is reformed. The quantity sulphuric acid, therefore, remains constant and only water disappears.

† Engelhardt. *Met. & Chem. Eng'ing*, Vol. XI, p. 43.
Palmaer and Brinell. *Met. & Chem; Eng'ing*, Vol. XI, p. 197.

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In the same way with caustic soda, NaOH, as electrolyte, the cathodic reaction is

$$2Na^{\cdot} + 2H_2O = 2NaOH + H_2, \quad (36)$$

and the anodic reaction is

$$2OH = H_2O + O, \quad (37)$$

so that H_2 is set free at the cathode and O at the anode, water disappearing, while the quantity of caustic soda remains constant, since as much is formed at the cathode as is decomposed by the current. It is, therefore, necessary to add new water to the solution from time to time. The decomposition e.m.f. of water with polished platinum electrodes is about 1.7 volts.

226. In a commercial electrolyzer the e.m.f. is 3 volts or less. We will assume 3 volts, 100,000 coulombs evolve 1.04 g. of hydrogen gas, occupying 11.6 liters at 0 deg. cent. and atmospheric pressure, and 8.3 g. oxygen gas, occupying 5.8 liters. But the passage of 100,000 coulombs at 3 volts represents an energy consumption of $\frac{1}{3}$ kw-hr. so that the electrolytic production of 1 cu. m. of hydrogen gas (0 deg. cent. and atmospheric pressure) requires somewhat over 7 kw-hr. With an acid solution the electrodes may be made of lead, with an alkaline solution of iron. In the construction of the vats for electrolysis the chief problem is to keep the hydrogen and oxygen gases separate from each other by some such device as a diaphragm.*

227. An important application of electrolytic hydrogen and oxygen is the production of high temperatures by the **oxyhydrogen flame**† for welding, etc.

ALKALINE CHLORIDE ELECTROLYSIS

228. Products of alkaline chloride electrolysis. If the solution of an alkaline chloride (say, sodium chloride) in water is **electrolyzed, the products may be, according to the arrangement** of the operation, either (a) caustic soda and chlorine, or (b) hypochlorite (bleaching liquor) or (c) chlorate.

229. Caustic soda and chlorine.‡ The total reaction is

$$NaCl + H_2O = NaOH + H + Cl. \quad (38)$$

At the cathode the Na cations discharge, react with water and form caustic soda and hydrogen gas. At the anode chlorine is liberated which is partly dissolved in the solution and partly evolved as gas. If the valuable products of the process are to be caustic soda and chlorine,§ the chief requirement is to keep the anodic and cathodic products separate from each other and to remove them as quickly as possible from the sphere of electrolytic action.

230. Mercury cathode processes. Of the mercury cathode processes the Castner-Kellner process and the Solvay process first achieved large industrial importance. The sodium-mercury alloy formed at the cathode of the electrolytic cell is by some special means removed from the surface of contact with the electrolyte and carried off to a separate cell where the amalgam is decomposed in contact with water, caustic soda, NaOH, being formed with simultaneous evolution of hydrogen gas, $Na + H_2O = NaOH + H$. In some mercury-cathode processes this is simply a chemical reaction, heat being evolved in consequence of its taking place. In other processes, like the Castner-Kellner, it is made an electrolytic action, and the energy given out by this reaction is obtained in form of electrical energy so that less energy is required to decompose the NaCl solution in the other cell. As a matter of fact, we have in this case two electrolytic cells in series. In the series: carbon anode, NaCl solution, mercury, water, iron cathode, the mercury acts as a bipolar electrode, and the reaction in the first cell is $NaCl + Hg = Cl + Hg,Na$, that in the second cell $Hg,Na + H_2O = Hg + NaOH + H$; hence the total reaction $NaCl + H_2O = Cl + NaOH + H$. The

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*See V. Engelhardt's "Electrolysis of Water," English translation by J. W. Richards, also *Met. & Chem. Eng'ing*, Vol. IX, p. 475.

† Concerning this and oxy-acetylene welding see R. N. Hart, "Welding."

‡ Billiter, "Die Electrochemischen Verfahren der Chemischen Grossindustrie;" Brochet, "La Soude Electrolytique;" Lucion, "Electrolytische Alkalichloridserlegung mit flüssigen Metall-kathoden;" Allmand, "Applied Electrochemistry, p. 342 to 385.

§ The hydrogen gas evolved at the cathode is usually wasted, though it is employed in Germany to some extent for balloon filling.

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it partial reaction consumes energy, hence it requires that a certain volt- e be impressed on the cell from the outside. The second partial reaction olves energy. Hence the total reaction requires energy equal to the ference of the energies of the two partial reactions. The voltage at the minals of the whole is less than that required for the first partial reaction one.

Newer mercury cathode cells are the Whiting cell and* the Wilderman l.† The advantages of mercury cathode cells are high purity and high ncentration of caustic soda with reduction of evaporation charges, and gh ampere-hour efficiency. The drawbacks are comparatively high volt- e and the first cost of the mercury.

231. Fused-lead-cathode process. While in the mercury-cathode cell aqueous solution of sodium chloride is electrolyzed, the fused-lead- thode process (C. E. Acker) employs an electrolyte of fused sodium loride. The sodium alloys with the fused lead. This alloy is carried off d decomposed in another vessel by means of a jet of steam. The principle exactly analogous to the mercury-cathode process (C. E. Acker, *Trans- tions* American Electrochemical Society, Vol. I, p. 165). The process no longer in commercial operation.

232. In the Glocken process or bell-process or gravity-process the anode contained in a bell-formed non-conducting receptacle, open at the bottom id thereby in connection with the outside cathode compartment surround- g the bell. By force of gravity the anodic and cathodic products are held tomatically separate and prevented from mixing and are continually rried off. Fresh saturated NaCl solution is continually supplied to the ode compartment (bell) and passes downward and prevents the OH ions om reaching the anode (O. Steiner, *Electrochemical and Metallurgical dustry*, Vol. V, p. 171).

233. In the Billiter-Leykam cell‡ the bell process has been modified by acing the cathodes (hooded to collect the hydrogen) immediately under- ath the bell jar, and not around its sides.

234. In the diaphragm processes§ which are the oldest ones and of which ere are quite a number, the electrolytic cell is divided into an anode com- rtment and a cathode compartment by means of a porous diaphragm hich prevents the mechanical mixing of the two solutions. If the chloride lution is supplied to the cathode compartment, the solution cannot be ghly saturated with caustic without trouble being produced by the OH ns passing to the anode. The only large industrial process in which this rangement is used is the Griesheim Elektron process‖ used in Germany. In most **other diaphragm cells** saturated sodium chloride solution is troduced into the anode compartment so as to flow through the diaphragm ward the cathode and counteract the tendency of the OH ions to pass to e anode. This is the case, for instance, in the cells of LeSueur, McDonald id others. A comparatively very small cathode compartment of special nstruction is the feature of the Hargreaves-Bird cell. This principle is rried still further in the Townsend cell, in which the cathode compartment ntains no electrolyte whatever, but liquid kerosene. The caustic as soon formed is absorbed in the kerosene and carried off. (C. P. Townsend, *ransactions* American Electrochemical Society, Vol. VII, p. 63; L. aekeland, *Electrochemical and Metallurgical Industry*, Vol. V, p. 209 id Vol. VII, p. 313.)

Almost all diaphragm cells use vertical diaphragms. An exception is e Billiter-Siemens & Halske cell¶ in which horizontal diaphragms are used.

235. Data on alkali-chlorine cells. Allmand ("Principles of Applied lectrochemistry," p. 383) gives the following comparative table of electro- emical data of different alkali-chlorine cells, which holds for those condi- ons under which the cell in question is normally worked. Concerning

* *Transactions* Amer. Electrochem. Soc., Vol. XVII, p. 327.
† *Met. & Chem. Eng'ing*, Vol. XI, p. 628.
‡ *Met & Chem. Eng'ing*, Vol. XI, p. 20.
§ Theory by Guye, *Jour. Chim. Phys.*, Vol. I, pp. 121 and 212, Vol. II, p. , and Vol. V, p. 398.
‖ Lepsius. *Chem. Zeit.*, Vol. XXXIII, p. 299.
¶ *Met. & Chem. Eng'ing*, Vol. XI, p. 19.

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figures of cost of operation see Engelhardt, *Met. & Chem. Eng'ing.*, Vol. IX, p. 489; also du Faur, *Met. & Chem. Eng'ing.*, Vol. VIII, p. 575.

236. Table of Chlorine-Alkali Cells (Allmand)

Cell	Normality of alkali	Cathodic current efficiency	Voltage	Energy efficiency	Kw-hr. per kilo NaOH
		per cent.	volts	per cent.	
Castner (rocking cell)...	5n.	92	4.2	50	3.1
Kellner (platinum anodes).	5–6n.	97	5.0	45	3.4
Kellner (carbon anodes).	5–6n.	95	4.5	49	3.1
Whiting.....	5n.	92	4.0	53	2.9
Wildermann.....	5–6n.	97	5.0	45	3.4
Griesheim (carbon anodes).	1–2n.	70–80	3.6	45–51	3.0–3.4
Griesheim (magnetite anodes).	1–2n.	70–80	4.0	40–56	3.3–3.8
Outhenin-Chalandre....	(2n.?)	66	3.7	41	3.7
Bell cell.....	2n.	85	4.0	49	3.1
Billiter bell cell.....	3n.	92	3.1	68	2.3
Billiter diaphragm cell..	3–4n.	95	3.7	59	2.6
Hargreaves-Bird.....	3n. Na_2CO_3	85	3.7	.....	.....
Townsend.....	4n.	94	4.8	45	3.4
Finlay.....	2n.	98	3.0	75	2.0

237. Anodes. Artificial graphite anodes are exceedingly useful. Platinum anodes are occasionally used. Ferric oxide electrodes have been introduced in Germany. The construction of concrete tanks for chlorine electrolysis is described by D. H. Browne, *Electrochemical Industry*, Vol. I, p. 273. Concerning the construction of diaphragms see Allmand "Applied Electrochemistry," p. 154.

238. Concerning the uses of electrolytic chlorine see F. Wirtenson, *Electrochemical Industry*, Vol. II, p. 339; O. Nagel, *Electrochemical and Metallurgical Industry*, Vol. III, p. 16. The chief application of electrolytic chlorine is for the manufacture of chloride of lime (bleaching powder). Other applications are the detinning of tin scrap (with production of tin tetrachloride), manufacture of carbon tetrachloride, sulphur chloride, acetylene tetrachloride, hydrochloric acid (by combining the anodic chlorine with the cathodic hydrogen), etc. Concerning the uses of chlorine in metallurgy see Baker, *Transactions* American Electrochem. Soc., Vol. XII. During the World War large quantities were used as poison gas, also for making phosgene and mustard gas.

239. Table of Hypochlorite Cells (Allmand)

Type	Brine used	Grams active chlorine per liter	Kw-hr. per kilo active chlorine	Kilos of salt per kilo active chlorine	Addition
	Per cent.				
Kellner (vertical electrodes).	15	12.0	6.5	.....	K_2CrO_4
Haas-Oettel.....	17	12.3	6.4	14	.....
Schuckert.....	15	20	6.0	7.8–8	Sodium resinate
Kellner (horizontal electrodes).	15	25	6.0	4–6	Sulphur compound

240. Hypochlorite (bleaching liquor). While for the production of caustic and chlorine by electrolysis of sodium chloride the anodic and

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hodic products must be kept separate, the reverse requirement must be illed for the electrolytic production of hypochlorites (bleaching liquors) electrolysis of sodium chloride. Sodium hypochlorite is the result of the ction of chlorine on caustic soda. To obtain the hypochlorite in the trolytic cell itself, the electrodes are placed near together and the electre- is maintained in steady motion in order to mix the anodic and cathodic ducts together. For a description of commercial cells for the production bleaching liquor see W. H. Walker, *Electrochemicol Industry*, Vol. I, 439; Engelhardt and Abel, "Hypochlorite and Elektrische Bleiche," olumes; Allmand, "Applied Electrochemistry," pp. 318 335. Concerning t of operation see Engelhardt, *Met. & Chem. Eng'ing*, Vol. IX, p. 489. Allmand's table (Par. 239) gives typical results yielded by different elec- lyzers. They cannot be very closely compared, owing to varying con- ions, but give an idea of the relative capabilities of the different types. Concerning the Digby hypochlorite cell see *Met. & Chem. Eng'ing*, Vol. , p. 328.

141. Chlorate. The production of chlorate by electrolysis of sodium loride requires interaction between caustic soda and chlorine under the nditions of a moderately high temperature, above 40 deg. cent. and an esence of reducing conditions. For the latter purpose the addition of romate has been found especially useful. No diaphragms are used in odern chlorate cells (see the German monograph by Kershaw and Huth; so Allmand, Applied Electrochemistry, pp. 335–341). As to the use of ectrolytically produced acid and alkali (obtained by electrolysis of a solution chlorate or perchlorate of sodium) for producing bichloric phosphate rtilisers see Palmaer, *Met. & Chem. Eng'ing*, Vol. X, p. 581.

ELECTROLYSIS OF CHLORIDES OF COPPER, NICKEL AND ZINC

142. Reduction of copper-nickel matte. Besides the electrolysis of kaline chlorides, which is now carried out on a very large industrial scale the numerous processes sketched above, chloride electrolysis has also been tempted in the metallurgy of copper, nickel and zinc. (Concerning the rly work of Hoepfner in this field see Wm. Koehler, *Electrochemical*

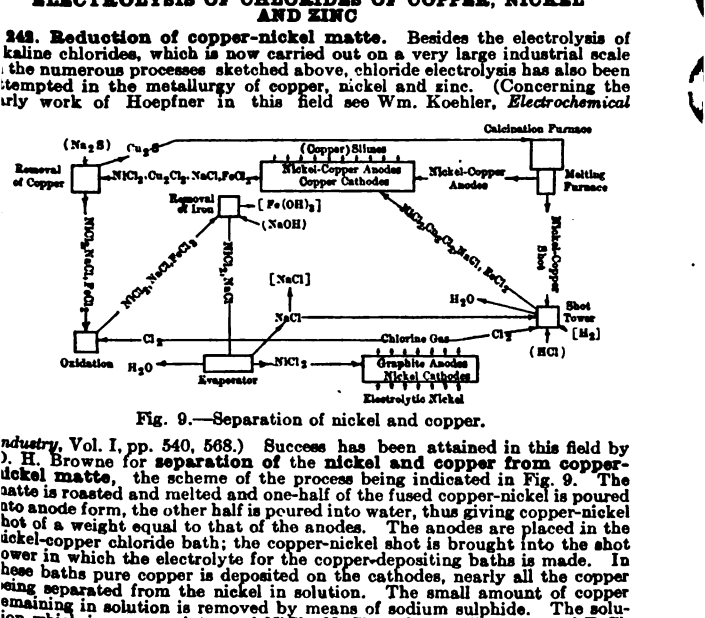


Fig. 9.—Separation of nickel and copper.

ndustry, Vol. I, pp. 540, 568.) Success has been attained in this field by). H. Browne for **separation of the nickel and copper from copper-ickel matte**, the scheme of the process being indicated in Fig. 9. The natte is roasted and melted and one-half of the fused copper-nickel is poured nto anode form, the other half is poured into water, thus giving copper-nickel hot of a weight equal to that of the anodes. The anodes are placed in the ickel-copper chloride bath; the copper-nickel shot is brought into the shot ower in which the electrolyte for the copper-depositing baths is made. In hese baths pure copper is deposited on the cathodes, nearly all the copper eing separated from the nickel in solution. The small amount of copper emaining in solution is removed by means of sodium sulphide. The solu- ion which is now a mixture of $NiCl_2$, NaCl, and a small amount of $FeCl_2$

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is then treated with some chlorine gas in order to oxidise the ferrous chloride to ferric chloride. By means of sodium hydroxide the iron is then removed from the solution; after removal of the ferric hydroxide, the solution is a mixture of $NiCl_2$ and NaCl and is then brought into the evaporator. The sodium chloride separates out, and the nickel chloride solution is subjected to elect olysis. As shown in the diagram, the process is nearly cyclic with respect to chlorine. (For details see F. Haber, *Electrochemical Industry*, Vol. I, p. 381.)

243. Fused chloride electrolysis is employed in the Swinburne-Ashcroft "chlorine-smelting" process for the treatment of mixed sulphide ores. The scheme is indicated in the diagram, Fig. 10, where the ore is assumed to be a mixture of zinc sulphide and the sulphides of two other metals, designated by M and N. The mixture of sulphides is first treated in the "transformer" with chlorine and changed into a mixture of chlorides. The second step of the process consists in substituting zinc for M and N. The zinc chloride is then electrolysed. The process is cyclic with respect to chlorine. (See Swinburne, *Electrochemical Industry*, Vol. I, p. 412; Vol. II, p. 404. See also Ashcroft's articles on experiments with fused electrolytes and handling of chlorine (pumping, etc.), *Electrochemical and Metallurgical Industry*, Vol. IV, pp. 91, 143, 178, 357.)

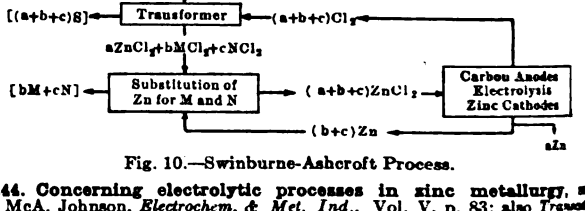


Fig. 10.—Swinburne-Ashcroft Process.

244. Concerning electrolytic processes in zinc metallurgy, see W. McA. Johnson, *Electrochem. & Met. Ind.*, Vol. V, p. 83; also *Transact.* Amer. Electrochem. Soc., Vol. II; and J. W. Richards, *Transact.* Amer. Electrochem. Soc., Vol. XXV. See also Günther's "Darstellung des Zinks auf Elektrolytischem Wege."

245. In gold metallurgy electrochemical processes have been tried or used in various ways. In the chlorination process electrolytic chlorine or electrolytically produced bleaching powder has been employed. In the cyanide process electrolytic precipitation of gold (as a substitute for zinc precipitation) by the Siemens & Halske process has been formerly employed on a large scale, especially in South Africa.* Clancy† has proposed the substitution of cyanamide (in combination with electrolysis) for cyanide, but has not achieved commercial success so far. Electrolytic amalgamation‡ has been experimented with repeatedly, but is not in use on a large scale at present; the principle is to make the mercury in the ordinary amalgamation process cathode of an electrolytic cell.

ELECTROLYTIC REDUCTION OF ALUMINIUM, SODIUM, MAGNESIUM AND CALCIUM

246. Aluminium. Finally, various electrolytic processes must be mentioned which have resulted in the cheap production of certain metals which can be made by other means only at great expense. The classical example is the electrolytic production of aluminium which is now certainly

* Concerning this process and its later developments by Butters, Hamilton and Richmond see *Electrochem. & Met. Ind.*, Vol. II, pp. 55, 131, 207, 215, 372. B. Neumann, Vol. IV, p. 297. C. R. Richmond, *Eng. & Min. Jour.*, 1907 March 16. See also Walker, *Transact.* Amer. Electrochem. Soc., Vol. IV, p. 47 and two papers by Kern and by Clevenger and Hall in *Transact.* Amer. Electrochem. Soc., Vol. XXIV, pp. 241, 271.

† *Met. & Chem. Eng'ing*, Vol. VIII, pp. 608, 623; Vol. IX, pp. 21, 230.

‡ Carey, *Met. & Chem. Eng'ing*, Vol. VIII, p. 438; *Transact.* Amer. Electrochem. Soc., Vol. XIX, p. 127.

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most important electrochemical industry. In the processes of Hall Héroult the electrolyte is a fused solution of alumina (as solute) in the ble fluoride of aluminium and sodium (as solvent). Carbon anodes are d, while the melted aluminium metal in the bottom of the pot forms the ıode. The temperature is 900 deg. cent. The alumina is decomposed the current and fresh alumina is added at intervals to the bath. Accord- to J. W. Richards the production of 1 kg. of aluminium requires 22 kw-hr. minium is used for the manufacture of various utensils, for all purposes ire lightness is an advantage, and especially for electric conductors as ubstitute for copper. J. W. Richards' "Aluminium" is the standard k on this metal; concerning the theory of the process a different view is ended in the book by Minet, translated by L. Waldo.* According to the S. Geological Survey, the production of aluminium in the United States 61,281 lb. in 1890; 920,000 lb. in 1895; 7,150,000 lb. in 1900; and 11,347,000 1905. It is estimated that the output in 1919 was 225,000,000 lb., but cial figures are not made public by the only producers, the Aluminum mpany of America.

247. Properties of aluminium cells. The property of aluminium trodes to let electricity pass in one direction (when the aluminium trode is cathode), but not in the other, is made use of in **electrolytic tifiers.** A. Nodon ("Transactions of the International Electrical ngress," St. Louis, 1904, Vol. I, p. 510) employs a neutral solution of monium phosphate in water as the electrolyte, with aluminium as one trode and the other electrode of lead or polished steel. C. F. Burgess l Carl Hambuechen (*Transactions* American Electrochemical Society, I, p. 147) use a fused electrolyte of molten sodium nitrate with an alu- ium and an iron electrode. If two aluminium electrodes are used, the tem represents an **electrolytic condenser** (C. I. Zimmerman, *Trans- ions* of the American Electrochemical Society, Vol. VII, p. 309). This ve effect of the aluminium electrode is also made use of in the **electrolytic htning-arrester** (see R. P. Jackson, *Electrical Journal*, August, 1907).

248. Metallic sodium is produced on a large scale by the **Castner ocess** from a fused NaOH electrolyte at a temperature not more than 10 15 deg. cent. above the melting point (which is at 308 deg. cent.). A ise or screen is provided between the electrodes and a superposed dome collecting the metallic sodium.

249. The Ashcroft process produces **sodium** from common salt in a ible cell of the following construction. In the first half of the cell fused ium chloride is electrolysed with a carbon anode (at which chlorine is rated) and a fused lead cathode (which absorbs the sodium). The same ed sodium-lead alloy forms the anode in the second half of the cell, fused OH being the electrolyte and the cathodes consisting of iron or nickel. this second half of the cell sodium passes from the sodium-lead alloy into bath and is deposited at the cathode, the fused bath remaining of con- nt composition. The first half of the process is in principle analogous the Acker process, the second half to the Castner process, but with exception that as much NaOH is re-formed at the fused sodium-lead ide as is decomposed. The total result of the process is given by the simple ation $NaCl = Na + Cl$ (*Electrochemical and Metallurgical Industry*, Vol. p. 218). (A good summary of various sodium processes is given by C. F. rrier, Jr., in *Electrochemical and Metallurgical Industry*, Vol. IV, pp. and 475; also *Met. & Chem. Eng'ing*, Vol. VIII, p. 253.) The yearly pro- tion of sodium in the world (1906) is about 3,500 tons, of which 1,500 tons used for making cyanide, 1,500 for peroxide and 500 are sold as metal.

250. Magnesium is produced by electrolysis from a fused dehydrated h of carnallite, *i.e.*, a double chloride of potassium and magnesium, or m a fused bath of magnesium chloride (Tucker and Jouard, Transact. ier. Electrochem. Soc., Vol. XVII, p. 249).

251. Calcium is made by a process of the Allgemeine Elektricitats sellschaft by electrolysis of fused calcium chloride, the cathode being tinually and slowly raised during process of electrolysis so that its end ays just touches the surface of the bath (J. H. Goodwin, *Electro-*

* See also Neumann and Oesen, *Met. & Chem. Eng'ing*, Vol. VIII, p. 185; ober, Vol. IX, p. 146.

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chemical and Metallurgical Industry, Vol. III, p. 80); Frary, *Transact.* Amer. Electrochem. Soc., Vol. XVIII, p. 117.

253. Concerning the electrolytic preparation of cerium see Hinde *Transact.* Amer. Electrochem. Soc., Vol. XX, p. 57.

DISCHARGE THROUGH GASES

253. Discharges through atmospheric air. If an electric discharge is passed through a gas or a mixture of gases, different chemical reactions are produced according to the nature of the discharge. Thus, if a silent discharge is passed through atmospheric air the oxygen (O_2 molecules) in the air is changed into ozone (O_3 molecules). On the other hand, if a spark or arc discharge passes through air, the oxygen and nitrogen of the air are forced to combine; since the nitrogen in the air is thereby fixed in form of a useful compound, this process is spoken of as the fixation of atmospheric nitrogen.

254. The rationale of ozone formation by the silent discharge is not yet fully understood although considerable evidence has been produced to the effect that the reaction is essentially photo-electric, due to the ultraviolet radiation which accompanies the silent discharge. It is known that ultra-violet rays passing through oxygen gas change it into ozone. Commercial ozonisers are operated by high-tension alternating current and the chief feature of their design is the necessity to avoid any spark or arc discharges. In most forms of ozonisers this is accomplished by providing a dielectric (glass, mica, etc.) between the electrodes. In the Siemens & Halske ozoniser* a water-cooled metal tube is employed in a glass or mica tube wound with copper ribbon; the glass or mica tube forms the dielectric, while the inner metal tube and the outer copper ribbon form the two electrodes. Through the annular space between the two the air to be ozonised is passed. In the Vosmaer ozoniser no dielectric is used, but the production of sparks and arcs is prevented by purely electrical means, essentially with the aid of condensers.

255. The main applications of ozone are for bleaching, purifying, sterilising, and for the industrial manufacture of certain chemical compounds such as vanillin from iso-eugenol. The chief application is for the sterilisation of water; its effectiveness for this purpose is certain but the cost of the process has, so far, somewhat restricted its wider application on a commercial scale.† (Sec. 22.)

256. Concerning other chemical effects of the silent discharge see for instance, J. N. Collie, *Transactions—Journal* of the Chemical Society, London, 1905, p. 154; Wiechmann, "Notes on Electrochemistry," p. 8. Concerning the fixation of atmospheric nitrogen by arc discharges see Pp. **260** to **268**.

FIXATION OF ATMOSPHERIC NITROGEN

257. Atmospheric air is a mixture of 80 per cent. by volume of **nitrogen** and 20 per cent. of **oxygen**, if the other gases which are present only in small quantities are neglected. Air is a mixture of gases, not a chemical compound. The importance of the problem of the fixation of atmospheric nitrogen rests in the fact that elementary nitrogen, as contained in the air, is inert and practically useless, while nitrogen compounds are of great commercial and industrial value, especially in the fertiliser industry and in the manufacture of explosives. The object of the "fixation" of atmospheric nitrogen is to change the elementary nitrogen in the air into some useful nitrogen compound. As there are various useful nitrogen compounds several fixation processes are possible. These will be discussed under the following three headings: nitric acid and nitrates; calcium cyanamide; nitrides and ammonia.

258. Nitric acid and nitrates. The simplest fixation process which suggests itself is to take the oxygen and the nitrogen in the air, as they are, and combine as large a portion of them as possible directly into nitrogen oxides (burning the atmospheric nitrogen) and then convert these oxides into nitric acid and nitrates. This is done in the processes of Bradley and

* The Siemens ozone plant for water purification in St. Petersburg is described by Erlwein in *Met. & Chem. Eng'ing*, Vol. IX, p. 213.

† An excellent serial, by A. Vosmaer, on the brush discharge, the production of ozone and its various uses, has been published in *Met. & Chem. Eng'ing*, Vols. XI and XII.

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ejoy, Birkeland and Eyde, Schoenherr (Badische Company) and Pauling, f which use electric discharges through air to produce a very high perature. The object of the spark or arc is simply to produce the very temperature required for the combination of the nitrogen with oxygen, h would go on in the same way if the same high temperature was pro- d by some other means. The gas mixture of air and nitrogen oxides thus uced is then treated with water or with alkaline solution (caustic soda, water, etc.) to give dilute nitric acid, nitrates, or a mixture of nitrates nitrites.

The higher the temperature, the greater is the content of nitric oxide pro- ed in the air and the quicker is the transformation. This is the reason the electric arc is so effective. Besides the necessity of producing a temperature, the second chief requirement is to remove the nitrogen e formed as quickly as possible from the high temperature zone and to it down as rapidly as possible; the reason is that with decreasing tem- tures the opposite reaction takes place and the nitric oxide dissociates into ogen and oxygen, so that if the cooling of the mixture of air and nitric e is too slow the latter will break up into its constituents. Haber has wn, however, that at low temperatures the formation of nitrogen oxide means of electric discharges cannot be considered as a purely thermal nomenon; there seems to be a specific electric effect superposed upon it. the temperature used in the commercial processes the thermal theory ched above seems to hold strictly true.*

9. In the Bradley-Lovejoy process† mechanical means (rotation of a el carrying one set of electrodes which continually pass along an opposite stationary set of electrodes) are employed to make and break continu- y sparks (6,900 sparks per sec.) in the space through which the air assed. While this process, which was tried for some years at Niagara s without attaining final commercial success, represents the era of the k furnace, the desire to get larger units led to the construction of arc aces. The different types differ essentially in the way by which the duced gas mixture is quickly removed from the gas zone.

0. In the Birkeland-Eyde process‡ the arc is deviated magnetically means of a single-phase magnet field, until the arc breaks; then a new is formed, etc. The Birkeland-Eyde process has been in successful mercial operation since 1905 in Norway (electric energy being very cheap be plant, 0.094 cent per kw-hr.).

1. The Schoenherr furnace. The Badische Company used success- y for a time the Schoenherr furnace,§ the characteristic feature of which e use of a very long alternating-current arc around which the air moves helical path. This plant has been taken over by the Birkeland-Eyde rests which now use principally the Birkeland-Eyde furnace, as it has gher efficiency in larger units.

2. Pauling process. Two plants in Tysol and in France employ Pauling process,‖ using electric discharges quite similar to those obtained horn lightning arrestor. The results obtained in these three commercial cesses were given in 1909 as follows (no later data being available):

	Grams HNO_3 per kw-hr.	Concentration in per cent. NO
nönherr	75	2.5
rkeland-Eyde	70	2
uling	60	1 to 1.5

For a concise summary of the thermodynamical principles of the problem , for instance, *Mineral Industry*, Vol. XIX, p. 58; also Guye, *Electro- m. & Met. Ind.*, Vol. IV, p. 136.

Electrochem. Ind., Vol. I, pp. 20 and 100.

Electrochem. Ind., Vol. II, p. 399; Vol. IV, pp. 295 and 360; Vol. VII, pp. , 305; *Met. & Chem. Eng'ing*, Vol. IX, pp. 340, 364, 436, 545; Vol. X, p. 617

Electrochem. & Met. Ind., Vol. VII, p. 245; *Met. & Chem. Eng'ing*, Vol. p. 73.

Electrochem. & Met. Ind., Vol. VII, p. 430; *Met. & Chem. Eng'ing.*, . IX, pp. 99 and 196. Concerning an experimental plant in North Carolina *Met. & Chem. Eng'ing*, Vol. VIII, p. 555.

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263. Calcium cyanamide,* $CaCN_2$ (lime nitrogen; German: Kalk stickstoff; French: Chaux Asotée), is made from calcium carbide and nitrogen (Frank and Caro), the fundamental reaction being

$$CaC_2 + N_2 = CaCN_2 + C$$

In this process the nitrogen must first be separated from the oxygen in the air (for instance, by fractional distillation of liquid air). Cyanamide may be used directly as a fertiliser, or as a starting material for making other compounds, like ammonia sulphide and nitric acid. Cyanamide may be made to make ammonia by blowing steam over cyanamide, $CaCN_2 + 3H_2O = CaCO_3 + 2NH_3$ and passing the ammonia so produced into sulphuric acid for the production of ammonium sulphate. Another development is the working of the ammonia (produced from the cyanamide as just described) into nitric acid by the Ostwald contact process.†

264. Nitrides and ammonia. The most interesting of the processes accomplishing the fixation of atmospheric nitrogen by means of nitrides is the Serpek process,‡ which is being tried on a large experimental scale in France. Its principle is first the production of aluminium nitride AlN from a mixture of alumina and carbon in an electrically heated kiln, in an atmosphere of nitrogen or producer gas ($Al_2O_3 + 3C + N_2 = 2AlN + 3CO$) at a temperature between 1,600 and 2,000 deg. cent.; this is followed by the decomposition of the aluminium nitride by water or caustic soda solution, thereby liberating the nitrogen as ammonia and producing an alkaline aluminate solution from which pure alumina can be obtained ($2AlN + 3H_2O = 2NH_3 + Al_2O_3$). The original intention was to use the alumina thus obtained for the production of fresh aluminium nitride so that the process would be cyclic with respect to alumina, and the net result would be the production of ammonia (by addition of the above two equations representing the two steps the result is $3C + N_2 + 3H_2O = 3CO + 2NH_3$). However, the production of aluminium nitride does not work well with pure alumina. The intention is now to produce simultaneously pure alumina and ammonia and to use the former alumina for the production of aluminium.

Another process for obtaining ammonia from atmospheric nitrogen is the Haber process§ for the synthesis of ammonia from its elements nitrogen and hydrogen. This process has no electrochemical features except possibly the production of hydrogen by the electrolysis of water.

A useful summary of the subject of utilisation of atmospheric nitrogen (covering proposals and accomplishments, unsuccessful and successful processes) is given by Thomas H. N. Norton in Dept. of Commerce & Labor Special Agents Series, No. 52 ("Utilisation of Atmospheric Nitrogen").

ELECTROMAGNETIC AND ELECTROSTATIC PROCESSES

265. Magnetic ore separators. Although not strictly electrochemical the application of electricity and magnetism to ore dressing may here be mentioned. There is no real chemical effect, but only a concentration or separation of a finely crushed ore-mixture into its constituents. The principle of magnetic separators is to pass the finely divided ore mixture through a strong magnetic field; the magnetic particles are thereby separated from the non-magnetic ones, since the latter are simply acted upon by gravity, while the former are attracted away from their path by the magnetic field. When they have been separated, they are called magnetic concentrates. A good summary of the practice of magnetic concentration, with description of magnetic separators and special reference to applications in zinc metallurgy may be found in W. R. Ingalls' "Report of the Commission Appointed

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* *Electrochem. & Met. Ind.*, Vol. V, p. 77 and Vol. VII, pp. 212, 305, 360. Concerning the thermochemistry of the formation of calcium cyanamide see Thompson, *Met. & Chem. Eng'ing*, Vol. VIII, pp. 617 and 6[illegible]. Concerning the definition of cyanamide see Beckman, *Met. & Chem. Eng'ing*, Vol. IX, p. 17.

† *Iron and Coal Trades Review* (London), May 23, 1913; *Met. & Chem. Eng'ing*, Vol. XI, pp. 438, 476.

‡ Tucker & Read, *Transact.* Am. Electrochem. Soc., Vol. XXII, p. [illegible]; Richards, *Met. & Chem. Eng'ing*, Vol. XI, pp. 137 and 281; Tucker, *Met. & Chem. Eng'ing*, Vol. XI, p. 139; Fraenkel, *Zeit. f. Electrochemie*, Vol. XI, p. 362.

§ *Met. & Chem. Eng'ing*, Vol. X, p. 637: Vol. XI, p. 211.

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stigate the Zinc Resources of British Columbia" (Canadian Government ication, 1906, pp. 82 to 118) and in C. G. Gunther's book on "Electro-netic Ore Separation." See also Ruhoff, *Met. & Chem. Eng'ing*, Vol. X, 78.

6. Electrostatic ore separators. The action of electrostatic separa- depends on the difference in electric conductivity of the constituents of ore mixture. According to the conductivity, the electrostatic charge ired by the different constituents from the same source of electric charge ne same time is different. If the mixture consists of a finely crushed conductor and a finely crushed conductor and is brought in contact with arged surface, the latter will receive a charge while the former remains arged. Electrostatic repulsions of the charged particles from the ged surface will then result, while the uncharged particles are not lled. (See paper by Blake in *Electrochemical and Metallurgical Indus-* Vol. III, p. 181; MacGregor, *Transact.* Am. Electrochem. Soc., Vol. II, p. 267, and Vol. XXIV; Wentworth, *Met. & Chem. Eng'ing*, Vol. , 167.)

7. Dust precipitation by electrostatic means. The Cottrell ess* is based on the old familiar phenomenon of the "electric wind." If etallic needle point is placed opposite a flat metallic plate and the needle is nected to one pole and the plate to the other pole of a high-voltage direct- ent supply line, electricity streams out of the needle point and charges the molecules in the space between needle and plate. The gas molecules receive an electric charge of the same sign as the needle point, hence osite to the sign of the charge of the plate. They are, therefore, attracted he plate and move toward it. Now if the space between the needle point the plate is filled with a gas or fume in which particles of dust, etc., are ended, these dust particles will be immediately charged with electricity will, therefore, move toward the plate, stick to it and give up their ges. The speed of movement of the particles is proportional to their ge and to the electrostatic field intensity in the space between point and e. Cottrell uses this principle for the precipitation of dust particles smelter fumes, etc. He employs ordinary commercial high-voltage rnating-current and converts it into intermittent direct-current by means specially designed synchronous converter. This intermittent direct-cur- is directly used for charging the system of electrodes (needles and plates) he flues which carry the gas under treatment. Instead of using needle its he twists asbestos filaments or mica scales with wires. The electricity es from the wires by surface leakage over the asbestos or mica, and the filaments of the asbestos or edges of the mica provide the required (very discharge points. The process is in successful use in smelters,† cement nts,‡ etc.

8. Smoke prevention. The same principle has been proposed for the ric precipitation of smoke (A. F. Nesbit, Elec. Rev., Oct. 31, 1914, p. 877).

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9. One of the best all-around books in English on industrial electro- nistry is Allmand's "Principles of Applied Electrochemistry." Other ral books are N. Monroe Hopkins, "Experimental Electrochemistry;" G. McMillan and W. R. Cooper, "A Treatise on Electro-metallurgy;" Mollwo Perkin, "Applied Electrochemistry;" M. de Kay Thompson, plied Electrochemistry."

very good general book on electric furnaces is Stansfield, The Electric nace. The application in the iron and steel industry is well treated in enhauser and Schoenawa, The Electric Furnace in the Iron and Steel stry (translated by vom Baur). Lyon, Keeney, and Cullen's, The Elec- Furnace in Metallurgical Work (Bureau of Mines, Bull. 77) is very useful. standard work on the theory and practice of the electrolysis of aqueous tions is Foerster's Elektrochemie wässeriger Lösungen. An equally llent work on fused electrolytes is Lorenz's Elektrolyse geschmolzener e, 3 vols. Neither book is available in English.

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Cottrell. *Met. & Chem. Eng'ing*, Vol. X, p. 172.
Bradley. *Met. & Chem. Eng'ing*, Vol. X, p. 686.
Schmidt. *Met. & Chem. Eng'ing*, Vol. X, p. 611.

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270. Footnote references throughout the section cover the liter of the subject in a very complete manner. In particular see footnot Pars. **3, 8, 64, 70, 71, 72, 78, 85, 87, 88, 97, 105, 121, 122, 127, 129 131, 132, 134, 194, 195, 196, 197, 199, 200, 201, 202, 203, 205, 208 226, 229, 230, 233, 234, 245, 246, 255, 258, 259, 260, 261, 262, 263 265** and **267.**

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SECTION 20

BATTERIES

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REVISED UNDER DIRECTION OF THE EDITOR

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SECTION 20

BATTERIES

PRIMARY BATTERIES

GENERAL THEORY

1. Definitions. An electric battery is a device for the direct transformation of chemical energy into electrical energy. The term is usually applied to an assembly of identical units or cells, connected in series. In a primary battery, the chemically reacting parts require renewal, whereas in a storage battery, the reactions being reversible to a high degree, the chemical conditions are restored after partial or complete discharge by reversing the current flow, *i.e.*, by electric charge. A primary cell is composed of a containing jar, plates or electrodes with suitable connecting terminals and the electrolytic solution. In certain types of cells, the two electrodes are in different electrolytes, separated by a porous cup.

2. The poles of a cell are the junctions of the external circuit with the plates or electrodes, *i.e.*, the terminals. The positive pole is that from which the current flows into the external circuit; the negative pole is the opposite terminal, and in the various practical primary cells, this is the zinc plate. Nevertheless, the zinc or **electrode** connected to the negative pole is termed the positive plate or electrode. It is the electrode that furnishes positive ions in the action of the cell and it is also usually the more important source of the chemical energy.

3. The e.m.f. of a cell is understood to mean its total electric pressure. If current is permitted to flow, the terminal difference of potential or the voltage is less than the e.m.f. by the amount of drop due to internal resistance, and also by the effects of polarization and concentration changes in the electrolyte.

4. The e.m.f. of polarization is the amount by which the total e.m.f. of a cell is reduced, when current flows, by secondary reactions or by concentration effects in the electrolyte at the poles. For example, if current is allowed to flow in the elementary zinc-dilute acid-copper cell, hydrogen appears at the copper electrode, the hydrogen-covered copper acting as a hydrogen electrode, to reduce the initial pressure of the cell. When a polarised cell is allowed to stand on open circuit, its voltage will return to nearly the normal value provided the active materials of the cell have not been exhausted.

5. Transition resistance. With certain electrodes and electrolytes the action of the cell results in the deposition of a relatively insoluble or insulating substance on the electrode surface. The effect of this is to increase the internal resistance of the cell.

6. Depolarizers. The effect of polarization at an electrode surface may be partly or almost completely eliminated by depolarizing means, which may be either chemical (Par. 7), physical or mechanical. Mechanical depolarization arises from a relative motion of the electrolyte and the plates. It is not employed in practical forms of cells. Physical depolarization results from roughening the electrode surface in order to give it greater area, or it may result from the electro-deposition of a loose mass of metal on the electrode surface, such as platinum black on a smooth platinum surface, etc. The hydrogen escapes more easily from such a surface, and the polarization is considerably reduced.

7. Chemical depolarizers. These are of two general types. In The electrolyte contains the ion of the metal which constitutes the negative plate, so that, when current flows through the cell, additional metal is deposited on the negative with no escape of hydrogen gas. An example is

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he copper sulphate in contact with the copper plate of a Daniell or gravity ell, or the slightly soluble mercurous-sulphate paste of the standard Clark or Weston cell.

(b) A chemical compound is present at the negative plate, which is apable of furnishing negative ions to the solution because of its metal onstituent possessing different valencies. Examples are the manganese eroxide of the Leclanché or dry cell and the chromic acid of the bichromate ell. It is of advantage that such depolarisers be relatively insoluble, n order that they may not come in contact with the zinc electrode and thereby uffer reduction.

8. Measurement of internal resistance and polarisation. The rue internal resistance of a cell is obtained from the formula

$$r = \frac{(E - E_p) - V}{I} \quad \text{(ohms)} \qquad (1)$$

n which E is the total e.m.f. of the cell on open circuit, E_p is the opposing olarisation e.m.f. and V is the voltage at the cell terminals. If immediately fter breaking the current, the cell voltage is determined by the condenser-allistic galvanometer method, or otherwise, then $E_p = E - V$.

Upon open circuit, after the delivery of current, the opposing e.m.f. of olarisation decreases, at first rapidly and then more slowly, owing o the gradual diffusion of the polarising substances. The curves, Fig. 1, are typical of a dry cell. The heavy curve shows the gradual drop in voltage, the cell being losed through a constant resistance, while the dotted curve read in the opposite direction) hows the voltage recovery, with ime, after the current ceases. The vertical portion of the recovery curve represents the voltage drop due to internal resistance, the further recovery being due to the gradual equalisation of concentrations throughout the electrolyte, or in the pores of the electrodes.

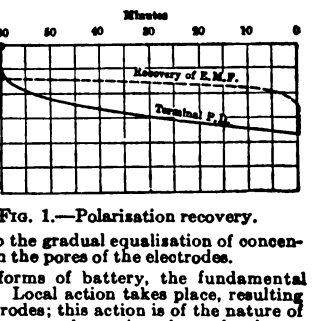


FIG. 1.—Polarisation recovery.

9. Local action. In all practical forms of battery, the fundamental eactions are somewhat departed from. Local action takes place, resulting rom impurities on one or both the electrodes; this action is of the nature of n elementary short-circuited cell. For example, a zinc electrode always ontains impurities such as copper, iron and carbon. Zinc is dissolved, ydrogen gas comes off at the point of impurity, and current flows between he impurity and the point where the zinc enters into solution. This action s reduced by **amalgamating** the surface of the zinc with mercury; this orms a solution of zinc, uniformly covering the surface, and greatly reduces he local action.

10. Electrochemical theory. Two methods may be employed in he theoretical consideration of primary battery phenomena. One, the eneral thermodynamic method, the other, a mechanical method resulting rom the osmotic-pressure theory of solutions. The e.m.f. of a reversible ell may be calculated from the relation

$$E = \frac{JQ}{nF} + T\frac{dE}{dt} \quad \text{(volts)} \qquad (2)$$

Where J = mechanical equivalent of heat = 4.19 joules; Q = heat of reaction in gram calories corresponding to the chemical change which takes place; n = number of equivalents involved in the reaction in which Q is the heat effect; F = electrochemical equivalent = 96,540 coulombs = a Faraday; T = absolute temperature in degrees centigrade. The first term of the right side of the equation is the controlling one, the second usually having a small value. If a cell has zero temperature coefficient the second term is zero. It may be either positive or negative. The above equation assumes the cell is reversible, but the voltage of any cell may be closely approximated by its use.

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11. Nernst's equation. The osmotic pressure theory of solutions (see Sec. 19) leads to the equation

$$E = 0.0002T\left(\frac{1}{n}\log\frac{P}{p} - \frac{1}{n'}\log\frac{P}{p'}\right) \quad \text{(volts)} \quad (3)$$

where T = absolute temperature n and n' are the valencies of the two ions of the electrodes and p and p' the osmotic pressures of these ions in the electrolyte. P and P' are the solution pressures. The solution pressure is the measure of the tendency of a substance to go into solution. In this theory, which is essentially mechanical, the seat of conversion of the chemical to electrical energy is clearly at the electrode surfaces.

12. Potential difference between electrode and electrolyte. In the preceding equation the two terms on the right-hand side are the difference of potential between the corresponding electrode and the electrolyte. It is apparent that the voltage of any cell depends on the concentration of the salts of the electrode metals present in the solution.

The absolute differences of potential of each element in a normal solution of one of its salts may be determined by means of a capillary electrometer, and the solution pressures of that element may then be calculated. However, the values of the solution pressure thus determined are open to some question.

13. Reference electrodes. In Sec. 19, Par. 174, the normal hydrogen and calomel electrodes are defined. They may be used as reference electrodes. The differences of potential between the normal hydrogen electrode and many elements when in normal solutions of their salts have been determined.

14. Electrochemical series. The various elements in normal solutions of their salts may be arranged in a series with reference to their potentials against the normal hydrogen electrode (see Sec. 19, Par. 175). It should be noted that the tabulated values and the order of the potential differences are dependent upon a normal strength of solution. If the elements are immersed in other electrolytes, the values will be quite different. The reader is referred to Le Blanc: *Electrochemie*, 1911, for a complete treatment of this subject. The series is not to be confused with the "Volatic series" nor with the "Peltier effect."

15. Potential rise and fall in a cell. The changes in potential in passing through a cell may be represented diagrammatically as shown in Fig. 2, in which the lines AB and CD are supposed to join at B and C. Starting at A and going in the direction of current flow, $ABCD$ represents the potential drop in the external circuit. DE is the potential rise which takes place in the film of electrolyte adjacent to the positive plate or negative pole. EF is the potential drop in the electrolyte between the plates. FA is the potential rise in the film adjacent to the negative plate or positive pole. The thickness of the films in which the potential rises take place are exceedingly small as calculated by the osmotic pressure theory.

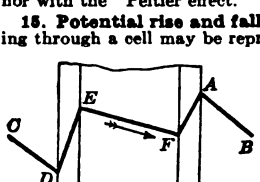


FIG. 2.—Potential diagram.

16. Concentration cells. An effect which is small, but which cannot be neglected is the difference of potential which exists at the boundary surface of two solutions of different concentrations. This arises through diffusion of the various ions tending toward equalisation of the concentrations on either side of the boundary and the fact that the different ions have different mobilities, that is, under unit force they move at different rates. See Sec. 19, Par. 145 et seq. This effect does not, however, lead to cell constructions of a practically valuable difference of potential.

17. Classification. Primary cells may be classified as wet and dry. They are further classified according to the method adopted for depolarisation and as to whether they are one or two fluid cells. The various applications of primary batteries impose special conditions which the different types in general use possess in very different degrees. Dry cells or storage batteries have displaced the other forms of battery to a great extent, although the gravity battery and the Edison Lalande battery have a wide application.

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WET CELLS

18. The Daniell cell. The container is usually a glass jar in which is a porous cup. A sheet of copper partly surrounds the outside of the porous cup and is in a saturated solution of copper sulphate containing excess crystals. The zinc (usually amalgamated) is in the porous cup, which contains sulphuric acid and zinc sulphate solution. The e.m.f. of the cell depends on the concentration of the zinc sulphate in the porous pot, the maximum initial value being about 1.14 volts. The cell may be set up with zinc sulphate solution only in the porous cup, in which case the e.m.f. is approximately 1.07 volts and has a very small temperature coefficient. The chemical reaction is $Zn+CuSO_4=ZnSO_4+Cu$. The cell is not adapted to stand on open circuit. When placed out of service the liquids should be poured out and the porous cup should be thoroughly washed in running water until all the zinc sulphate is removed, otherwise the cup will crack on drying.

19. Gravity battery. This cell is the usual modification of the Daniell cell, and is shown in Fig. 3. The porous pot is omitted and gravity is depended upon to keep the heavier copper sulphate solution in the bottom of the cell. The zinc is frequently cast in the form of a "crowfoot" and hangs from the edge of the jar. The copper electrode is made of two or three strips of sheet copper, riveted together and spread out in the bottom of the jar. A rubber-covered wire is fastened to the copper and leads upward out of the cell. Copper-sulphate crystals are placed in the bottom of the jar and zinc sulphate solution is added to cover the zinc. The solution should be poured in carefully, so as not to bring the copper sulphate solution in contact with the zinc, as copper would be immediately precipitated on the zinc.



FIG. 3.—Gravity cell.

20. Care of gravity battery. The cell should be kept on closed circuit in order to prevent copper from diffusing upward and precipitating upon the zinc. The edge of the jar should be coated with paraffin to prevent creepage of the zinc sulphate solution. As the top solution becomes saturated with zinc sulphate some of it should be drawn off and carefully replaced with water. The copper sulphate solution must not be stirred up. Evaporation may be reduced by covering the solution with a thin layer of mineral oil. If a heavy copper precipitate is present on the zinc, it should be scraped off. A sharp dividing line should be maintained between the two solutions. This can be noted by color difference. At the top should be a light colored solution, while the copper sulphate is very dark blue. For each ampere hour, the following amounts of materials are theoretically used up or formed—0.042 oz. copper deposited, 0.043 oz. zinc dissolved, and 0.164 oz. copper sulphate used up. Local action will require at least a 10 per cent. greater amount of zinc and copper sulphate. Note that the increased copper weight should be credited to the cost of upkeep.

21. Bunsen or Grove cell. In the Bunsen cell the zinc plate is in a sulphuric acid solution, while the negative plate is a carbon rod immersed in strong nitric acid, contained in a porous cup. The Grove cell differs from the Bunsen cell only in the use of platinum instead of the carbon. The e.m.f. of this type of cell is about 1.9 to 2 volts and the internal resistance quite low. The cell is adapted for laboratory purposes and can be used for heavy currents. It must not be allowed to stand on open circuit for any considerable time, and must be set up freshly each time it is used.

Vapors of nitric peroxide are given off from the cell and provision must be made for their removal. The chemical reaction of the cell is represented by the equation $Zn+H_2SO_4+2HNO_3=ZnSO_4+2H_2O+2NO_2$.

22. Chromic-acid cell. This cell is in wide use for laboratory purposes. It may be used as a single-fluid cell but the porous-cup form is preferable. The Grenet or plunger type is shown in Fig. 4. Two carbon plates are immersed in a solution of potassium or sodium bichromate, sulphuric acid and water. Potassium permanganate is a fairly satisfactory equivalent to the chromic-acid salt. The zinc plate is between the two carbons when lowered for use. The usual solution is made up as follows: water, 12 lb.

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concentrated sulphuric acid, 2½ lb. and potassium bichromate, 1 lb. Potassium bichromate gives rise to insoluble crystals of chrome alum and the sodium salt is preferable. Chromic acid, on account of its great solubility is to be preferred over either of the above salts, and the quantity used need be but two-thirds of the weight of either of the salts, required for the same effect. The cost of the equivalent weight of the chromic acid is not appreciably greater than the salts. The e.m.f. of the cell is about 2 volts, and the



FIG. 4.—Grenet chromic-acid cell.



FIG. 5.—Fuller cell.

internal resistance extremely low. It can therefore be used for high currents and, by raising the zinc, can be open circuited. The chemical reaction is represented by the formula $3Zn+2CrO_3+6H_2SO_4=Cr_2(SO_4)_3+3ZnSO_4+6H_2O$.

23. Two-fluid chromic-acid cell. In the single-fluid type there is some local action between the zinc, and the chromic acid and a waste of both these materials even when the zinc is amalgamated. It is preferable

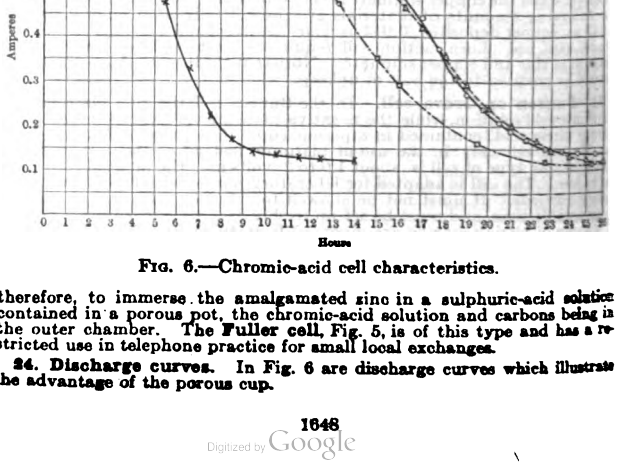


FIG. 6.—Chromic-acid cell characteristics.

therefore, to immerse the amalgamated zinc in a sulphuric-acid solution contained in a porous pot, the chromic-acid solution and carbons being in the outer chamber. The **Fuller cell**, Fig. 5, is of this type and has a restricted use in telephone practice for small local exchanges.

24. Discharge curves. In Fig. 6 are discharge curves which illustrate the advantage of the porous cup.

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25. Leclanché cell. There are many forms of this cell in practical use the original form the carbon rod was contained in a porous cup filled th crushed carbon and manganese dioxide, the mixture being tamped to tain intimate contact. In the later forms, the manganese dioxide and rbon are moulded by the use of a binder into a cylindrical form, the zinc d being suspended centrally, as in Fig. 7. The electrolyte is a solution salammoniac. The e.m.f. is about 1.5 volts, but the terminal voltage drops pidly with high currents. The cell is suitable for open-circuit or closed-cuit work, if large currents are used intermittently and for short periods time. The continuous current demand on closed circuit must not exceed a w hundredths of an ampere, as otherwise the terminal voltage is too greatly duced by polarization. The chemical reaction is $Zn+2NH_4Cl+2MnO_2$ $ZnCl_2+2NH_3+H_2O+Mn_2O_3$. The dry battery, which is a modification the Leclanché cell, has largely replaced the latter in practical use.

26. Edison Lalande. The usual form of this cell comprises a plate of compressed copper oxide on either side of which is a zinc plate with ribs. These s serve to hold the plate together until it is worn out. The copper-oxide ate is superficially reduced to cover it with a very thin layer of metallic pper for conductivity. The electrolyte is caustic soda solution covered th a layer of mineral oil to prevent evaporation and the formation of sodium rbonate from the carbon dioxide of the air. The construction of these lls is shown in Fig. 8. The chemical reaction is $Zn+2NaOH+CuO=$ $a_2ZnO_2+H_2O+Cu$. The e.m.f. of the cell is 0.95 volts and the terminal voltage drops to less than two-thirds of this value when furnishing heavy currents. Its internal resistance is low. It is adapted for both closed and open-circuit work and does not depreciate materially, except from the

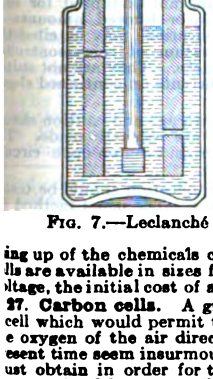


FIG. 7.—Leclanché cell.

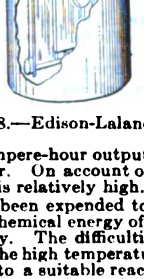


FIG. 8.—Edison-Lalande cell.

ing up of the chemicals corresponding to the ampere-hour output. These lls are available in sizes from 100 to 600 amp-hr. On account of the low ltage, the initial cost of a battery of these cells is relatively high.

27. Carbon cells. A great deal of effort has been expended to develop cell which would permit the conversion of the chemical energy of coal and e oxygen of the air directly into electric energy. The difficulties at the esent time seem insurmountable on account of the high temperature which ust obtain in order for the carbon to enter into a suitable reaction, and cause the CO_2 necessarily formed unites with the fused caustic soda electrolyte, which has been proposed. The difficulties in the way of an oxygen ectrode are also great.

28. Standard cells. The **Clark cell** has an electrode of mercury, ntaining metallic zinc, an electrolyte of zinc sulphate and a depolarizing ectrode of metallic mercury, covered with a paste of mercurous sulphate hich is only slightly soluble. The chemical reaction is $Zn+Hg_2SO_4=ZnSO_4+2Hg$. In the **Weston cell**, cadmium is substituted for the zinc. ery elaborate preparation of all the materials used in these cells is imperative, and the reader is referred to the extensive literature on this subject. he variation of the e.m.f. with temperature of the practical forms of these lls is given in Sec. 3. These cells are not adapted for closed-circuit work, though they quickly recover their voltage after an appreciable discharge.

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DRY CELLS

29. Definition. The only "dry battery" in commercial use is a modification of the Leclanché cell, in which the sal ammoniac solution is held by capillary action in a porous medium separating the zinc from the opposite electrode and in the pores of the carbon-depolariser electrode.

30. Construction. In the usual form, the zinc of the negative pole takes a cylindrical shape and constitutes the containing vessel. An absorbent separating medium of pulp, plaster of Paris or paste covers the walls and bottom of the zinc cylinder, and a rod or flat plate of carbon is placed axially inside. A mixture of crushed coke, graphite and manganese dioxide is tamped about the carbon rod to within about 1 in. of the top edge of the zinc cylinder. The whole is mounted in a pasteboard container and the filling mass saturated with a solution of zinc chloride and sal ammoniac. The top is then flooded with an asphaltum sealing compound. The stud of the positive binding post is fixed in a vertical hole in the carbon by running in an expanding bismuth alloy, the hole in the rod being enlarged at the bottom.

31. The internal resistance of various makes of dry cells depends slightly upon the absorbent material between the plates, but is principally determined by the fineness of the crushed carbon and manganese dioxide and the degree to which it is tamped when new. The internal resistance is usually less than 0.1 ohm but increases to several times the initial value with age.

32. The open-circuit voltage of a new cell is approximately 1.5 volts and is but slightly influenced by temperature. With age the voltage gradually drops, whether the cell is used or not. The terminal voltage on closed circuit is about 1 volt, the greater portion of the drop being due to polarisation. For this reason it is not usually important to determine the internal resistance.

33. Dry-cell applications. Dry cells are admirably adapted for such purposes as require minute currents continuously or limited amounts of current intermittently. Among the various applications may be cited the following: intermittent gas-engine ignition; operation of relay-controlled mechanisms; telephone work; pocket flash-lamps; etc. They are not suited for heavy discharges nor to furnish appreciable currents on continued closed circuit.

34. Life. Dry cells continuously depreciate with age and caution should be exercised when purchasing to see that cells are recently made. The better makes become worthless after 12 to 14 months, even on open circuit. A gage as to their condition is therefore desirable.

35. Dry-cell tests. Cells for any particular application should be tested under conditions which approximate actual service. The usual method for a large consumer is to place a number of cells in a rack and by means of resistances and switch contacts operated by a clock mechanism, subject the cells to intermittent discharge at the desired rates and for the desired intervals. Those interested in standard tests for dry cells should consult the report of the Committee of the American Electrochemical Society on Dry Cells, *Trans.* Am. Elect. Chem. Soc. Vol. 21, p. 275, 1912 and Circular No. 79, April, 1919 of the Bureau of Standards.

36. Shelf test. The user of a considerable number of dry cells should select a few at random for shelf test. This consists in determining the number of months the cells will last before the short-circuit current, taken at monthly intervals, falls to a certain arbitrary value which is customarily taken at 10 amp. Such test cells should be continuously kept at about 70 deg. Fahr., as the shelf life is favorably influenced by lower temperatures. Dry cells depreciate rapidly at high temperatures. Voltage readings on open circuit have little or no value in determining the merits of a cell.

37. Qualitative tests. It is desirable to apply rough selective tests if dry cells are purchased from any but reliable dealers. The best test of this nature is to connect a cell momentarily through a dead-beat ammeter which has been calibrated. For this test the resistance of the outside circuit, including the ammeter shunt, should be 0.01 ohm to within 0.002 ohm. According to Ordway (Trans. Am. Elect. Chem. Soc., 1910) a 2½ in. × 6-in. dry cell should, when freshly made, give between 18 and 25 amps. at a temperature of about 70 deg. fahr. If a cell gives less than 18 amps. age or

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eriority is indicated. Short-circuit tests are of real value only when the rmal short-circuit current is known for the particular brand of cell tested. ie mere fact that the short-circuit current of one brand of cell is less than at of another is no indication of inferiority in its service capacity. Short-cuit current bears no relation to service capacity as is shown by the follow-g table. (D. L. Ordway, *Trans.* Elec. Chem. Soc., 1910.)

Brand of cell	*A*	*D*	*G*	*J*	*M*	*P*	*V*	*X*
Short-circuit current	33.0	24.5	22.5	20.9	20.1	19.2	11.6	6.6
Ampere-hour capacity	24.0	33.5	40.0	18.2	11.7	30.3	13.6	4.5

38. Effects of temperature. Temperature has but small effect on the en-circuit voltage of dry cells but it has a marked influence on the rate their deterioration. In general, temperatures above 25 deg. cent. (77 deg. hr.) are injurious. The following table shows the effect of temperature the short-circuit current at the end of ten weeks for cells stored at differ-t temperatures. (Pretz, Am. Elect. Chem. Soc., Vol. 19, p. 39, 1911.)

Temperature		Per cent. decrease in short-circuit current	Temperature		Per cent. decrease in short-circuit current
Deg. cent.	Deg. fahr.		Deg. cent.	Deg. fahr.	
5	41	4.4	55	131	52.0
25	77	10.0	65	149	71.0
35	95	19.0	75	167	98.0
45	113	25.0	.....	.....	.....

39. Capacity. The capacity of a freshly made standard 2½-in. × 6-in. y cell, closed through a circuit of 16 ohms resistance, averages about 25 mp-hr. before the terminal voltage falls below 0.5 volts. Individual cells ay show considerably better capacity than this. The following table ven by D. L. Ordway (Trans. Am. Elect. Chem. Soc. Vol. 17, p. 352, 1910) ows the hours of service of the common size of dry cells (2½-in. × 6-in.) hen discharging continuously through resistances of fixed values before e voltage dropped to the stated values.

End-point voltage in volts	Resistance of the discharge circuit						
	2	4	8	16	24	32	40
1.2	4.3	10	39	142	260	414	549
1.0	9.3	35	94	296	548	889	1,148
0.8	16.5	51	143	414	751	1,078	1,550
0.6	28.2	76	225	954	1,240	1,600	1,763
0.4	55.0	207	648	1,197	1,711	2,280	2,040
0.2	160.0	450	882	1,318	1,914	2,626	3,140

40. Service tests. The committee on dry cell tests of the Am. El. hem. Society (Transactions 1912) recommended the tests described in ar. **41** to **43.**

41. For telephone work. Connect 3 cells in series through a resistance 20 ohms for a period of 2 min. during each hour until the terminal vol-ge falls to 0.93 volt per cell at the end of the 2-min. period. The sts are to continue 24 hr. per day and 7 days per week, and the number of ys elapsing until the above limiting voltage is reached is to be noted. his test has now been supplanted by the A. T. & T. test which is as follows: hree cells connected in series are discharged through 20 ohms for ten per-ds of four minutes each in ten consecutive hours for six days per week. n the seventh day every other period is omitted. The limiting end voltage the same as given in the Am. Elec. Chem. Soc. test. The results are pressed as the number of days the cells last.

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42. For gas-engine ignition. Connect 6 cells in series through 16 ohms resistance for two periods of 1 hr. each during each day, 7 days per week. The first discharge may be made during the morning, and the second, late in the afternoon. At the end of each twelfth of the above discharges, shunt the 16-ohm resistance with a 0.5-ohm resistance connected to an ammeter and note the current. The test is considered complete when the current through the 0.5-ohm shunt, at the end of any discharge period, falls below 4 amperes. The results are expressed as the number of hours actual discharge to the end point. This test has been somewhat modified by some manufacturers to permit the use of a smaller number of cells in the group.

43. For flash-lamp service. Discharge the battery through a resistance of 4 ohms for each cell connected in series for a period of 5 min. once each day, and determine the total number of minutes of actual discharge, the terminal voltage of the last discharge being limited to 0.75 volt per cell. At the present time 0.50 volt per cell is generally used for the end voltage instead of 0.75 because modern lamps are still usable at the lower voltage.

44. Standard sizes of dry cells. The standard sizes of the cylindrical form of dry cells are given below. (Circular No. 79, April 25, 1919, Bureau of Standards.)

For ignition, telephone, etc. (cylindrical form)		Flash light and miniature cells (cylindrical form)			
Diameter in inches	Height in inches	Diameter in inches	Height in inches	Diameter in inches	Height in inches
1⅛	4	⅞	1⅞	1	2⅛
2⅛	6	⅞	2⅛	1⅛	2⅛
3⅛	8	1⅛	1⅛	1⅛	2⅛

STORAGE BATTERIES

45. Definitions. Cells which are reversible to a high degree, i.e., those which the chemical conditions after discharge are brought back to the original condition simply by causing current to flow in the opposite direction, or "charge," may be used as storage batteries. Storage batteries are sometimes termed **electric accumulators.**

46. Reversibility. In all the practical forms of storage batteries, both the electrode materials and the products of the chemical reaction are relatively insoluble. The form of the electrodes is practically unchanged with use, or at least it changes but slightly. Many of the cells in which the reaction products are soluble and which are ordinarily used as primary batteries can be used as storage batteries. For example, the Daniell or gravity cell and also the Edison-Lalande cell are reversible to a high degree, but have practical disadvantages contributing against their use as storage batteries.

47. Classification. The storage battery which is in widest commercial use, for various purposes, is the lead-sulphuric-acid type. The only other type which is of any prominence is the nickel-iron-potash battery, apparently first proposed by Darrieus, then by Jungner and developed in commercial form by Edison. The use of cadmium instead of iron as a negative plate is due to Hubbell. His cell is otherwise similar to the Edison cell. It is extensively used in miners' lamps.

48. Positive and negative plates. The positive terminal or pole of a battery is that one from which the current flows into the external circuit. In storage battery practice, a positive plate is one which is connected to the positive pole, and the negative plate, the one which is connected to the negative pole. It should be specially noted that this is the reverse of primary-battery terminology. The U. S. Patent Office has attempted to avoid confusion in this regard by insisting on the use of the terms, "positive-pole plate" and "negative-pole plate," but this has not come into general use.

49. The e.m.f. or open-circuit voltage of any storage cell depends wholly upon its chemical constituents and not in any way upon the number

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total area of its plates. It varies further with the strength of the solution, electrolyte, and its temperature, and to a minor extent, with the state charge of the plates. Upon charge, the terminal voltage of the cell es, and, upon discharge, it falls, due to the internal resistance and to a mber of more or less obscure causes, such as polarisation, acid-concenation effects, etc.

50. The capacity of a cell with a definite type and thickness of plate in proportion to the plate area. The size of a cell is usually stated in rms of its ampere-hour capacity at a standard temperature of 70 deg. fahr., it it is necessary, also, to state the discharge rate, as the capacity of l practical forms of batteries is lower with increasing discharge rates.

51. Battery voltage. The voltage of a battery is that of each cell ultiplied by the number of cells connected in series.

LEAD STORAGE BATTERIES

GENERAL

52. Theory. The active material of the lead storage battery is lead roxide (PbO_2) on the positive plate or electrode and finely divided, or sponge ad (Pb), on the negative plate. The plates are immersed in a solution of ulphuric acid and water ($H_2SO_4 + H_2O$) called electrolyte. On discharge the battery, both these active materials are quantitatively converted to lead sulphate, ($PbSO_4$) at the expense of the acid radical of the electrolyte id with the formation of water. Precisely the reverse action takes place pon charge of the battery and these reactions may be represented by the llowing chemical equations:

Reaction at positive plate:

$$PbO_2 + H_2SO_4 = PbSO_4 + H_2O + O \qquad (4)$$

Reaction at negative plate:

$$Pb + H_2SO_4 = PbSO_4 + 2H \qquad (5)$$

Combined reaction at positive and negative plates:

$$PbO_2 + Pb + 2H_2SO_4 = 2PbSO_4 + 2H_2O \qquad (6)$$

Eq. (6), read from left to right, is the equation of discharge; read from right left it shows the reactions during charge. The above reactions are those hich normally take place. If impurities are present either in the plates emselves or in the electrolyte, these normal reactions may be departed om.

53. The active materials, lead peroxide on the positive plate and spongy ad on the negative plate, are crystalline in structure, the masses being held gether by the intergrowth of the crystals. The positive active material robably exists in the cell as a hydrated peroxide of lead; when fully charged has a very dark brownish-black color, but the color of the positive plate s a whole may be somewhat masked by the presence of loose particles of hite lead sulphate which have become detached from the active mass. he positive plate becomes reddish brown in color with proceeding discharge. The color of the negative active material is that of metallic lead fter it has been exposed to air, and is somewhat darker when the plate is ischarged. These active materials are supported on the plates in either f two ways. With Planté plates, they form rather dense, thin layers, ormed from a massive lead blank with a highly developed surface and dhere to the surface. With pasted plates the active materials are cemented asses supported in a grid, usually of lattice form.

54. The capacity of a cell is the number of ampere hours it is capable f giving at 70 deg. Fahr. when discharging at the normal rate before its oltage falls to some limiting value usually taken as 1.8 volts for the stationry type of cells. (See Par. 116.) Capacity depends upon many things uch as: type of plates, density of electrolyte, temperature and rate of discharge. The 8-hr. rate is standard with lead cells of the stationary type. Vo standard rate has been adopted for the other types.* The capacity f a plate varies with the amount of active material, but not directly, because its mass initially does not hold enough acid to convert it to lead sul-

* For standard rate proposed by Standards Committee, Soc. Automobile Engineers, for gas-car batteries, see Sec. 22.

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phate. Diffusion of acid into the mass is quite slow, so that the higher the discharge rate, the more nearly is the plate surface the determining factor. The capacity of a cell at the higher rates of discharge depends, therefore, on the area of its plates, their number, and, to a minor extent, on the thickness of plates. With low discharge rates, a sufficient amount of acid diffuses into the interior of the active material to permit this portion to be acted upon.

55. The amount of active material converted into lead sulphate per ampere-hour of discharge is 0.135 oz. (avoirdupois) of sponge lead, and 0.156 oz. of lead peroxide, independent of the discharge rate. Reduction of capacity with high rates is the result of using up the acid in the pores of the active material, and lack of time for fresh acid to diffuse from the electrolyte to replace it. Diffusion is also hindered by the reduction of porosity on the surface of the active materials, due to the formation of lead sulphate, which occupies a greater volume than either the sponge lead or lead peroxide. The amount of active material actually present in a plate is some three to six times that converted into lead sulphate, part of this excess being present for the life of the plates.

56. The open-circuit voltage of a lead cell varies between 2.06 to 2.14 according to the strength of electrolyte and temperature and is independent of the size of a cell. Charge and discharge characteristics are given under the descriptions of the various types of cells.

57. The variation of voltage is approximated by the following formula due to Streints:

$$E = 1.850 + 0.917(G - g) \qquad \text{(volts)} \qquad (7)$$

in which E = e.m.f. in volts, G = specific gravity of electrolyte, and g = specific gravity of water at the cell temperature.

58. Test or reference electrode. It is often desirable to determine the relative performance of the positive and negative plate groups in a cell and this may be done by taking the voltage between each group and a reference electrode of zinc, spongy lead or, preferably, cadmium.

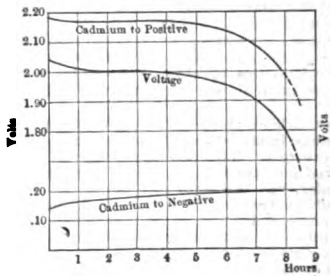


FIG. 9.—Discharge curves.

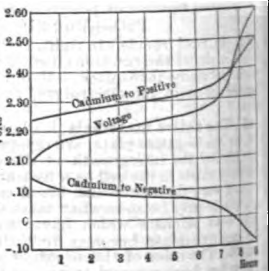


FIG. 10.—Charge curves.

59. A typical discharge curve for a stationary type of cell is shown in Fig. 9, also the curves for both positive and negative groups with reference to cadmium. Curve (1) shows the cell voltage, curve (2) the voltage of the positive group and cadmium, while curve (3) represents the voltage for the negative group and cadmium. Fig. 10 shows the corresponding curves for charge.

60. Cadmium tests. The cell voltage is the difference between the positive-cadmium and the negative-cadmium voltages. In Fig. 9 the discharge curves are continued in dotted lines and, the greater portion of the final voltage drop occurring with the positives, show that the capacity of the cell, in this instance, is limited by the positive group. This is a desirable condition, as most negatives suffer from overdischarge more than do the positives.

Care is necessary when using the cadmium electrode in order to obtain reliable results. The electrode should be thoroughly corroded before use

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aging several days in battery solution. Polarization of the cadmium ectrode due to voltmeter current may appreciably affect the voltage read-gs. It is greatest when measuring the cadmium-positive potential and, this case, may amount to as much as 0.1 volt when a voltmeter of 200 to 00 ohms resistance is used. It is much less when measuring the cadmium-gative potential and should not exceed 0.01 volt. To make the effect of olarisation negligible, the Bureau of Standards (Technologic Paper No. 46) recommends that the cadmium-positive potential be obtained indirectly y adding the cell voltage to the cadmium-negative potential.

61. Lead battery plates are classified thus: Planté plates (Par. **62**) and asted plates (Par. **64**).

62. Planté plates comprise a mass of lead, usually of flat form with a ighly developed surface. The increased surface is obtained by casting a ellular structure, or by scoring or cutting a blank of heavy sheet lead. The ctive material is electrochemically formed as a coherent layer of lead per-xide at the expense of a film of the underlying lead. Such plates are lways formed as positives, but Planté negative plates are obtained from the ositives by connecting them as negatives in a cell, and charging, whereby he active material is reduced to sponge lead.

63. The original Planté process of formation consists of charging the lates alternately in opposite directions; each successive reversal under roper conditions of temperature, strength of electrolyte and current in-reases the capacity of the plates. This method is extremely wasteful of urrent and requires a long time; it has been abandoned in favor of accelerated forming processes which consist of making the plate to be formed an node in an electrolyte of dilute sulphuric acid containing a small amount of nitric, perchloric or other acid which dissolves lead. The current density, trength of acids and temperature must be properly related to obtain a uccessful result.

64. Pasted plates take the form of a flat basket-like frame or grid, pasted with a mass of lead oxide under cementing conditions. After the mass is thoroughly cemented, the plates are assembled in a dilute sulphuric-acid electrolyte and charged. The oxide mass becomes lead peroxide on the positives and sponge lead on the negatives.

65. Processes in paste manufacture. There are many ways of making paste masses which have been proposed and great merits have been claimed for special processes. All the practical paste processes, however, depend in principle on the cementing action resulting from the formation of lead sulphate. Plates can be pasted with a stiff mixture of lead oxide and water and then immersed in dilute sulphuric acid solution. The resultant sulphating hardens the mass. Another method is to mix the oxide with dilute sulphuric acid or a solution of ammonium sulphate and stir to a uniform thick paste, which is then smeared into the grids quickly and before much sulphating has had time to take place.

66. Combination of Planté and pasted plates. Pasted plates of one polarity can be used with Planté plates of the opposite polarity and *vice versa*, but plates of different design or age should not be assembled together in any single positive or negative group in a cell. If this is attempted, local action takes place between the different plates.

67. Depreciation of Planté plates. Planté positive plates wear in service, by gradually shedding their active material and, as fast as this occurs, new lead automatically is corroded and formed to lead peroxide at the expense of the original reserve of metallic lead of the plate. The life of these plates is at an end when the lead becomes so corroded that the plate is mechanically weak. A good positive Planté plate is capable of giving 1,800 to 2,400 cycles of complete charge and discharge at the 8-hr. rate.

Planté negative plates in use show a physical shrinkage of their active material, and, associated with this, a shrinkage of capacity. Good Planté negatives have a capacity of 75 per cent. to 100 per cent. in excess of their rated capacity to provide against this factor. They should give 2,500 to 3,000 cycles of charge and discharge at the normal rate before falling to 80 per cent. of their rated capacity.

68. Depreciation of pasted plates. Pasted positive plates lose their active material by gradual shedding which, however, should not begin until

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after 60 to 70 cycles of charge and discharge. The capacity is maintained so long as there is sufficient remaining active material. Plates 0.25 in. thick should give 600 to 800 complete cycles of charge and discharge at the 8-hr. rate, before falling to 80 per cent. of their rated capacity. Plates 0.125 in. thick should give some 300 or more complete cycles of charge and discharge.

Pasted negative plates would show the same physical shrinkage of active material as Planté negatives, if it were not for the incorporation of materials such as lamp-black, barium sulphate or kaolin, termed **expanders**, into the oxide pastes. Pasted negatives can be somewhat thinner than pasted positives which have the same life.

69. Permanising process. Instead of mixing expanders (Par. 68) with the paste, certain substances can be deposited in the pores of the active material to produce a like result, after the plates are formed. Jca Bijur perfected a process of soaking negatives in sugar solution and subsequently carbonising the sugar. He also brought forward a process of precipitating barium sulphate in the pores of the spongy lead. The process is specially applicable to Planté negatives.

70. Growth of Planté plates. All Planté positives show the characteristic of growth in service. The lead peroxide occupies more volume than the lead from which it is formed, and this action finally causes the lead to stretch. For this reason, they are usually made of smaller dimensions than the negative plates with which they are used. In some cases, the growth takes place unequally on the two sides of the plate, thus causing a deformation or **buckling**. As the positives grow their capacity usually increases very appreciably.

Attempts have been made to reduce buckling of Planté positives by subdividing them and allowing for growth of individual sections. These methods have not proved very successful in practice and have largely been abandoned.

71. Tudor Positive. Fig. 11 is a "Tudor" positive. It is a cellular casting of pure lead. It has claimed for it the characteristic of remaining straighter in service than other Planté types and that it shows a minimum of buckling. No centre web is employed, an open type of construction being adopted.

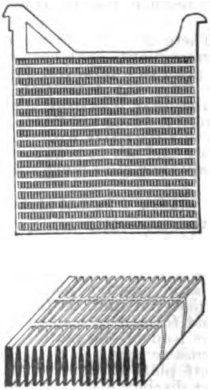


FIG. 11.—Tudor positive and section.

72. Centre-web positives. Figs. 12 and 13 show Planté positives made from a sheet-lead blank, the surface being increased by plowing leaves in the first



FIG. 12.—Willard "plowed" plate.

instance, and by **"spinning"** with rotating circular discs in the latter. A section of the latter plate is shown in Fig. 14.

73. Manchester positive. Fig. 15 shows a Manchester positive, comprising a casting of lead antimony with a number of round holes symmetrically spaced. Into these holes are inserted spiral coils of corrugated lead ribbon. The plate as a whole is electrochemically formed, but the frame

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work is only slightly corroded. This makes a very rugged plate. It will not show as good a life in possible number of cycles of charge and discharge as the pure-lead Planté plates, but this is largely counterbalanced by its rigidity. The plate is, however, much more sensitive to overcharge than are the other Planté plates.

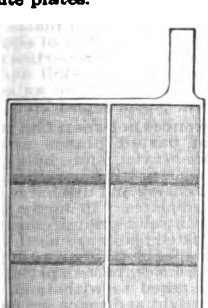


FIG. 13.—Gould "spun" plate.



FIG. 14.—Section of Gould "spun" plate.

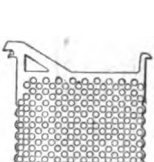


FIG. 15.—Manchester positive.

74. Planté negatives. Any of the foregoing Planté positives can be used as negatives by reversal, but the general form of Planté negative is that shown in Figs. 12 and 13, since these can most readily be given the required excess capacity.

75. Paste-plate grids. A section of the usual pasted-plate grid termed the shelf type is shown in Fig. 16 and a modification which is in considerable use in Fig. 17. The grids are cast of an antimony-lead alloy, the antimony content being sufficient to make the grids stiff. The presence of the antimony also serves, to a considerable degree, to limit the amount of corrosion which would otherwise take place on the positive grid in service.

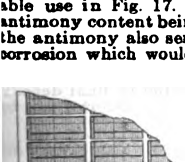


FIG. 16.—"Shelf type" grid.

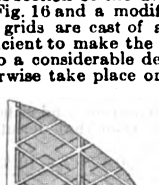


FIG. 17.—"Diamond" grid.

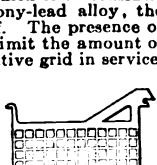


FIG. 18.—Box negative.

76. Box negative. A pasted plate which is in wide commercial use in stationary batteries is the box negative of the Electric Storage Battery Co. The grid is cast in two halves, the outside of each half grid consisting of a very thin perforated sheet lead. Loose pellets of oxide paste are dropped into one-half, the other half grid then being placed on top and both are riveted together. This plate is shown in Fig. 18.

77. Ironclad positive. Another type of pasted plate which is considerably used is the positive of the "Exide Ironclad" battery. This plate, Fig. 19, comprises a number of vertical pencils or units supported in a frame of lead-antimony alloy. Each pencil or unit has a central core of lead-antimony alloy of somewhat irregular section. A layer of lead peroxide sur-

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rounds this core and is retained by a slotted cylindrical casing of hard rubber. The slots are so small that the particles of active material do not readily fall out. It is claimed that the presence of the casing greatly increases the useful life of the plate. The Ironclad battery is used principally for traction purposes. See Par. **125**.

78. Quality of paste materials. Active materials of pasted plates vary in quality with the chemical purity of the oxides partly, but it is of equal or greater importance that the physical properties meet rigid specifications. A high degree of skill and accurate information is required to produce an active material having the requisite capacity and life.



FIG. 19.—Ironclad positive.

79. The essential differences between the practical forms of Planté and pasted plates are the following: Planté plates are heavier, more bulky and cost more for the same capacity. They will give a greater number of cycles of charge and discharge than can be obtained from pasted plates. In many cases weight and space are the controlling requirements to be met and in this case pasted plates are used. If a battery is required for insurance of power supply, and is used only in rare emergencies, pasted plates can be used. If a battery is required to withstand continued heavy service, and weight and space are not an important consideration, Planté plates are used.

80. Electrolyte variations. When a lead battery discharges, the amount of sulphuric acid which combines with the active materials is in quantitative proportion to the number of ampere hours discharged. The density of the electrolyte varies with its acid content, and the change in density may be used as a measure of the state of charge of the battery, if the initial and final specific gravities are known.

81. The quantity of electrolyte required for 100 amp-hr. discharge is calculated from the following formula.

$$G_o = \frac{1290 - 10.53d}{D - d} \qquad \text{(oz.)} \tag{8}$$

in which G_o = number of ounces of electrolyte per 100 amp-hr. of discharge; D = per cent. of H_2SO_4 in the electrolyte at the beginning of discharge; and d = per cent. of H_2SO_4 at the end of discharge. For a capacity G other than 100 amp-hr. multiply G_o by $G \div 100$.

When the value of G_o for 100 amp-hr. and either the initial or final density of the electrolyte are known, then that density which is unknown can be determined from the following:

$$D = \frac{1290 + d(G_o - 10.53)}{G_o} \tag{9}$$

and

$$d = \frac{1290 - G_o D}{10.53 - G_o} \tag{10}$$

82. The change in acid strength is not immediate; it lags behind the values determined in Par. **81** on account of the fact that time is required for the strong acid to diffuse into the plate on discharge, and for the strong acid to diffuse out of the pores of the active material on charge.

83. Separation. It is essential that plates of opposite polarity be kept from coming in contact with each other. This is insured by the use of ribbed perforated sheets of hard rubber, glass spacing tubes or, more frequently, wood **separators.** The wood used is selected for a minimum content of such constituents as would be injurious to the plates and it is usually subjected to a treatment to reduce such constituents still further. See Par. **126.**

84. Lead burning of joints. The use of solder must be avoided in storage-battery construction. Joints are made by lead burning, by which is meant the melting together of the lead parts by a hydrogen flame. This flame deoxidises the melted lead, and the two parts readily flux together.

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ELECTROLYTE AND WATER



FIG. 20.—Hydrometer.

85. The electrolyte used in lead storage batteries is a solution of sulphuric acid and water. The sulphuric-acid content determines the density of the solution, *i.e.*, its specific gravity (sp. gr.) or the ratio of its weight to that of an equal volume of water.

86. Hydrometer. The specific gravity of electrolyte is practically determined by the use of a hydrometer which consists of a weighted glass bulb with a graduated stem. In strong acid the stem protrudes further above the surface of the solution, and the point at which the top of the meniscus touches the scale is read off directly in degrees of specific gravity.

With stationary types of cells there is usually space enough between plates or at the end of the tank to float a flat-bulb hydrometer directly in the acid of the cell. This type of hydrometer is illustrated in Fig. 20.

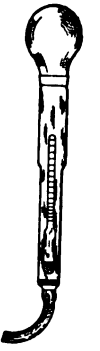


FIG. 21.—Syringe hydrometer.

87. Syringe hydrometer. With vehicle and other types of batteries with small separation between plates, a convenient method to determine the acid density is to employ a syringe hydrometer as illustrated in Fig. 21; the hydrometer floats within the enlarged portion of the glass barrel when acid is sucked into it by means of the rubber bulb.

88. Table of Sulphuric-acid Solutions

(Based on one part acid of 1.835 sp. gr. at 60 deg. Fahr.)

Specific gravity of solution (70 deg. Fahr.)	Parts of water to one part acid		Percentage of sulphuric acid in solution
	By volume	By weight	
1.100	9.8	5.4	14.65
1.110	8.8	4.84	16.0
1.120	8.0	4.4	17.4
1.130	7.28	3.98	18.8
1.140	6.68	3.63	20.1
1.150	6.15	3.35	21.4
1.160	5.7	3.11	22.7
1.170	5.3	2.9	24.0
1.180	4.95	2.7	25.2
1.190	4.62	2.52	26.5
1.200	4.33	2.36	27.7
1.210	4.07	2.22	29.0
1.220	3.84	2.09	30.2
1.230	3.6	1.97	31.4
1.240	3.4	1.86	32.5
1.250	3.22	1.76	33.7
1.260	3.05	1.66	35.0
1.270	2.9	1.57	36.1
1.280	2.75	1.49	37.3
1.290	2.6	1.41	38.5
1.300	2.47	1.34	39.65
1.320	2.24	1.22	42.0
1.340	2.04	1.11	44.1
1.360	1.86	1.01	46.3
1.380	1.7	0.92	48.4
1.400	1.56	0.84	50.5
1.500	1.0	0.55	60.15
1.600	0.639	0.348	69.12
1.700	0.369	0.201	77.6
1.800	0.1192	0.0646	87.5
1.835	0.0	0.0	93.19

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89. Mixing electrolytes. If concentrated sulphuric acid and water are mixed a great amount of heat is generated. If electrolyte is prepared from concentrated acid, the acid should be added to the water. Never add water to concentrated sulphuric acid. Mixing should be done in a glass or earthenware vessel or a hard rubber jar.

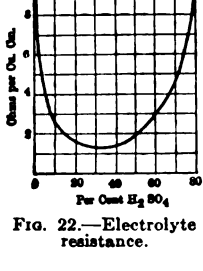


FIG. 22.—Electrolyte resistance.

90. Temperature. The density of electrolyte decreases with increased temperature on account of expansion, although the actual strength remains the same. A temperature of 70 deg. Fahr. is taken as standard, and since the specific gravity of electrolyte varies approximately 0.001 for each 3 deg. Fahr. difference in temperature, the specific gravity at any temperature within practical limits is reduced to that at standard temperature by adding or subtracting 0.00033 for each degree Fahr. above or below 70 deg.

91. The resistance of the electrolyte varies with its specific gravity and with temperature. The curve shown in Fig. 22 indicates that at the extremes of dilution or concentration the resistance is highest and is a minimum at a specific gravity of 1.224, or when the proportion of acid is 31 per cent. Its temperature coefficient is negative, the resistance decreasing with increase of temperature. Table (**92**) gives the resistance in ohms (cm.-cube) of electrolyte of varying densities and at different temperatures. It will be seen that the decrease of resistance with increase in temperature is very marked.

92. Table of Resistance of Electrolyte in Ohms (Cm.-cube) for Various Temperatures and Specific Gravities

Spec. grav. at temps. given	32 F.	47 F.	61 F.	75 F.
1100	1.43	1.122	1.00	0.91
1200	1.33	0.900	0.73	0.62
1300	1.35	1.000	0.79	0.43
1400	1.89	1.425	1.05	0.82

93. Freezing point of electrolyte. The freezing point of the electrolyte of fully-charged batteries is very low; however, the electrolyte of partly discharged batteries will freeze at low temperatures. When a mixture of sulphuric acid and water freezes, it does not become solid. It forms a slushy mixture and does not become hard until a lower temperature is reached. Although a battery may not be injured by freezing it should be protected against low temperatures unless it is fully charged. Even though the electrolyte does not become solid on freezing there is danger of cracking the jars. The freezing points of sulphuric acid solutions are given in the following table.

Sp. gr.	Temp. (deg. fahr.)	Sp. gr.	Temp. (deg. fahr.)	Sp. gr.	Temp. (deg. fahr.)
1.060	25	1.160	2	1.260	−75
1.080	22	1.180	− 6	1.280	−90
1.100	18	1.200	−16	1.300	−95
1.120	14	1.220	−31	1.320	−80
1.140	8	1.240	−51	.....	.....

The minimum freezing point occurs between specific gravities of 1.30 and 1.32.

94. New electrolyte. The presence of impurities in a cell is objectionable (Par. **99**). In acid used for the first filling of cells they should not exceed the limits cited in Par. **95**.

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95. Maximum allowable impurities in electrolyte for first filling (initial charge).

Color	Colorless
Suspended matter	Trace
Platinum	Trace
Antimony and arsenic	Trace
Manganese	0.0025 per cent.
Iron	0.005 per cent.
Copper	0.0025 per cent.
Nitrogen in any form	Trace
Chlorine	0.001 per cent.
Organic matter	None

96. Maximum allowable impurities in water used for replacing evaporation. In the operation of a battery, the electrolyte loses water by evaporation, also some water is electrolytically decomposed. Water must be added to the cells, and any impurities it might contain would be cumulative. The maximum limits of impurities in water for storage-battery purposes are given in the following table:

Color	Colorless
Suspended matter	Trace
Total solids	10 parts per 100,000
Calcium and magnesium oxides	4 parts per 100,000
Iron	0.05 parts per 100,000
Ammonia as NH_4	0.8 parts per 100,000
Organic matter	0.1 parts per 100,000
Nitrates as NO_3	1.0 parts per 100,000
Nitrates as NO_2	0.5 parts per 100,000
Chlorine	1.0 parts per 100,000

97. Water supply and storage. The use of distilled water is preferable, but frequently local sources of supply will meet the requirements. The different battery makers are usually glad to report on the suitability of waters from different sources if samples are submitted by users of their batteries. Otherwise, an analysis should be obtained from a competent chemist, if any doubt exists. A 2-quart sample in an absolutely clean glass or rubber-stoppered bottle should be submitted for this purpose. Well water is nearly always to be rejected, and hot well water from condensers usually contains impurities arising from cylinder oils or boiler compounds. Rain water is suitable if taken from clean roofs. Water should be stored so that it is not contaminated by dust or foreign matter, and, if chemical or ice factories are in the neighborhood, the possibility of absorption of acid or ammonia vapors must be guarded against.

98. Replacement of electrolyte. If the battery has been in service a long period and impurities have been accumulated through the use of impure water or otherwise, the electrolyte may require renewal. The table in Par. **99** will determine if this is required.

99. Maximum allowable impurities in electrolyte for batteries in service.

Color	Colorless
Suspended matter	None other than lead compounds
Platinum	Trace
Antimony and arsenic	Trace
Manganese	0.005 per cent.
Iron	0.01 per cent.
Copper	0.005 per cent.
Nitrogen in any form	Traces
Chlorine	0.002 per cent.
Organic matter	Trace

100. Effects of impurities. Of the impurities mentioned in Par. **99**, those which are metallic will be precipitated at once upon the negative

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plates if they are less electronegative than lead, and the electrolyte of a cell will not show anything more than traces of such impurities. Their presence is indicated, if, on open circuit, the negative plates of a cell gas continuously. Platinum is the worst of the metals in this respect.

The presence of iron and manganese compounds in electrolyte is decidedly injurious, as they are reduced to lower states of oxidation when in contact with the negative plates, and reoxidize when in contact with the positive plates—in both cases with the formation of lead sulphate from the active materials of the plates. The presence of nitrous or nitric acid or its compounds, or any chlorine compounds, is especially injurious, as these tend to corrode the unformed lead of the positive plates. Organic acid or organic matter which may readily be oxidized to acids, will act in the same manner.

The possible injuries resulting from the presence of iron, chlorine or nitric acid, are of much greater consequence in giving a battery its initial or developing charge. A high degree of purity of the electrolyte must, therefore, be assured before using it in new cells, if obtained from any other source than the battery manufacturer. Old cells will withstand much greater quantities of foreign substances.

101. Rough qualitative tests for the presence of iron or chlorine which are the more frequent impurities may be carried out as follows: Fill a test-tube to approximately one-third of its capacity with electrolyte, add one or two drops of dilute nitric acid and heat to the boiling point. Then allow the contents to cool and add ammonia solution until the acid is thoroughly neutralised. As soon as the solution does become neutral, a light brown, loose, flocculent precipitate of iron hydrate will indicate the presence of an appreciable amount of iron, in which case the electrolyte should be carefully examined for its iron content.

102. The qualitative test for chlorine is to fill a test-tube approximately one-third full of electrolyte, and add a few drops of a very dilute solution of silver nitrate. If the solution becomes opalescent, the electrolyte should be examined carefully for chlorine content. A great excess of chlorine will be indicated by the test solution becoming curdy.

TESTING

103. Preliminary. Before starting a test on a lead-acid type of storage battery, see that it is fully charged and in good condition. The acid should be pure and its strength adjusted to that which is recommended by the maker as standard for the type. If the battery is new, insure that it is fully developed by taking several preliminary discharges; the capacity of a battery increases very considerably with the first few cycles of charge and discharge. Before starting tests for capacity or efficiency, continue the charge at the normal or 8-hr. current rate for a stationary type of battery, or at the "finishing" rate (usually about one-half of the normal rate) for pasted plate batteries, until neither cell voltage nor acid density shows a further increase for four 15-min. intervals, which will indicate that the battery is fully charged.

104. Capacity tests. Since the capacity depends on the rate of discharge it will be advisable, with stationary types of batteries, to obtain test discharges at several different rates; in particular, those most nearly approximating the desired service conditions. Nearly all the makes of storage batteries will operate at the higher discharge rate if they give full capacity at the normal or 8-hr. rate. In conducting the usual tests, the charging should preferably take place at the normal rate. When the discharge is started the current should be maintained as steady as possible and should continue until the cell voltage has reached its limiting value. Voltage readings should be taken at stated intervals and the strength of acid, temperatures and possibly also cadmium readings should be taken at the same time. The same readings should be taken on the subsequent charge. It is advisable to plot these readings, as any discrepancies will then be apparent. The ampere-hour capacity of the cell will be the average amperes multiplied by the time of discharge in hours. The watt-hour capacity will be the ampere-hours multiplied by the average voltage of discharge, provided the current is maintained reasonably steady.

105. Characteristic performance. A complete series of tests as outlined in Par. **104**, carefully plotted, will give the battery characteristics

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ith a set of these curves, the performance of a battery can be quite definitely termined. It is of little value, from an engineering standpoint, to know e internal resistance of a cell, except for highly special applications, as e drop in voltage due to polarisation, usually greatly exceeds the resistance op. The expression **"virtual internal resistance,"** which is an atmpt to include polarisation effects, is also of no value, as it contains no time ctor, and the time the discharge is to last is of extreme importance.

106. An approximate way of determining the internal resistance a cell is to proceed as follows: Momentarily interrupt the current and note e instantaneous increase in cell voltage, preferably by the condenser-llistic-galvanometer method. The difference between the terminal volges with and without the current flow is the resistance drop; dividing this ference by the current will give the approximate value of the internal sistance. Values determined by the Wheatstone bridge method with alterting current will be in error on account of the capacity effect which any ctrode shows in an electrolyte.

107. Efficiency tests. The efficiency of a storage battery is the ratio watt-hours of discharge to watt-hours of charge and should be determined the mean of several charges and discharges, as there is no absolutely definite int to terminate either the charge or discharge. The condition to be met simply that the battery must have received sufficient charge each time to sure full capacity on the succeeding discharge. The efficiency should be ken as the ratio of the total watt-hours of discharge to the total watt-hours charge, for all the charges and discharges. For efficiency tests, the end int of charge should be taken as the point when both positives and negares are gassing uniformly, the voltage showing the same value for two readgs taken 15 min. apart, and the acid density having reached a value thin 0.003 deg. sp. gr. of the maximum value reached on the thorough ercharge before starting the test. The terminating point of discharge ould be taken as that at which the battery has discharged the desired mber of ampere-hours; the specific gravity of the acid, corrected for temrature, if necessary, should show approximately equal values at the d of each discharge. Failure to observe the above points, especially mperature effects, may cause serious errors in the determination. The om temperature should be maintained as nearly constant as practicable.

BATTERIES FOR STATIONARY PURPOSES

108. Batteries for power-plant purposes are usually designed with the ea that combined capital and maintenance charges shall be a minimum. For is reason, if a battery is in nstant active service, anté plates are used, but the main consideration is surance of continuous wer supply, or "stand-by" rvice, pasted-plate batter- will usually prove to be e more economical. sted-plate batteries are hter, require less room, st less, and, if but a limited mber of discharges are reired, they will have as g life as the Planté-plate tteries. Considerable atition is given to the de-

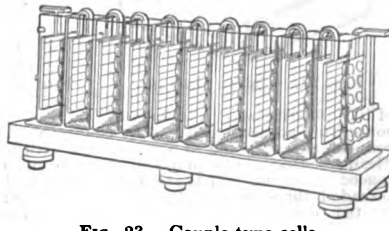


FIG. 23.—Couple type cells.

ls of stationary batteries in order to insure reliability and long life.

109. Plate sizes. For small requirements the **couple types** are plicable, the construction details being apparent from Fig. 23. The pacities available in this type are the following:

ize of plate (in.)....	3 by 4	4 by 4	5 by 5	6 by 6	5 by 8½	7½ by 7½
-hour capacity (ampere-hours).....	7	10	15	20	24	40

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For greater capacities with the regular cell constructions the following sizes of plates are used:

Size of plate (in.).....	7¾ by 7¾	10¼ by 10¼	15¼ by 15¼	18¼ by 18¼	15¼ by 31
8-hour capacity (ampere hours).....	40	80	160	240	320

110. Choice of plate size. As a general rule the smallest size of plate should be chosen which does not make the width of the cell prohibitive. It is also well to choose either of the first two sizes of the latter table if possible, as they may be mounted in glass jars, these being cheaper and more durable than the lead-lined tanks used with the larger sizes. Glass jars up to about 13¾ in. long by 12¾ in. wide by 18 in. high are readily obtainable from American manufacturers. Larger sizes have to be imported.

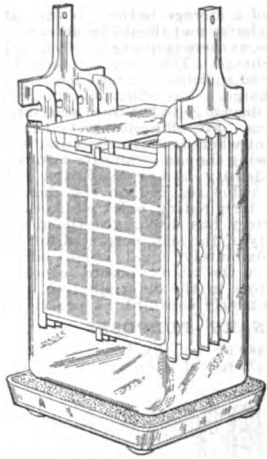


FIG. 24.—Cell in glass jar.

111. The standard glass jar mounting is shown in Fig. 24. The plates are provided with supporting lugs resting on the edges of the glass jar and the plates

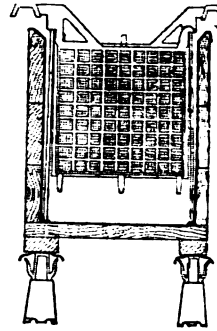


FIG. 25.—Cell in lead-lined tank

of like polarity are "lead burned" to a cross bar with connector straps for connecting adjacent cells. The connector straps are either joined by bolt connectors, consisting of a brass stud with lead-covered brass nuts, or are "lead-burned." The plates of opposite polarity are intermeshed and are spaced apart by **separators**, comprising diaphragms of wooden veneer threaded through slotted wooden dowels, both veneer and dowels being first treated to remove injurious substances. The veneers are fairly durable in the electrolyte but require renewal in 2 to 4 years. They prevent particles of active material bridging across the space between plates, which otherwise would cause internal short-circuits. The separators are kept from floating by pieces of glass called **separator hold-downs.** The cells are set in a layer of sand contained in a wooden sand tray thoroughly coated with asphaltum paint, and the sand trays are mounted on glass insulators. The use of porcelain insulators is to be avoided, as the glaze is attacked by acid spray and the insulating properties are lost. Glass sand trays with integral insulating feet are often used instead of the wooden trays and insulators. They are not satisfactory in the larger sizes on account of liability to breakage.

112. Lead-lined tank construction. Plates 15¼ in. x 15¼ in. and larger are always mounted in lead-lined tanks, the construction being shown in

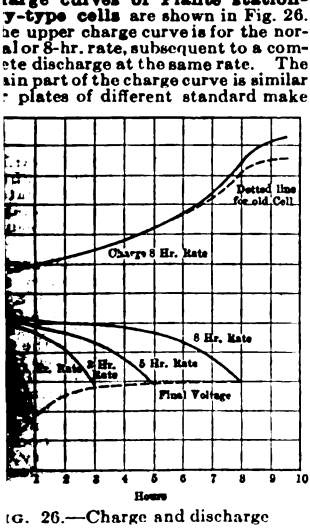
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ig. 25. **The wooden tanks** are preferably of long-leaf yellow pine, with dove-il joints and dowels and without metal fastenings. The tanks should be ainted both inside and outside with three coats of acid-resisting paint, and ied with 4-lb. sheet lead, the lining projecting outside the wooden nk in order to prevent acid falling onto the tank. Tanks should have a eral mud space to take the accumulation of sediment. The sediment space ould exceed one-third of the length of the plate. The tanks should be sup-rted on glass insulators, the oil-filled type with a protecting cover being referred. Lead footings are placed in the bottom of the tanks, upon which st the glass support plates. The support plates are about ½ in. thick, and ve the upper edges, which support the plate lugs, ground smooth. The ates are lead-burned to bus bars of extruded lead and wooden separators ith dowels are used to space the plates, as with the glass-jar cells. A few stallations of large cells have been made in special acid-proof stoneware nks, but this construction has not come into general use.

113. Erection. Glass-jar cells are mounted on wooden stringers, or two er racks if space is limited, these being thoroughly coated with acid-resist-g paint. The insulators for lead-lined tanks usually rest upon acid-sisting tile, the tiles being brought to a level by supporting them on pillars sulphur-sand cement. These piers are made by supporting the tile on a ll of stiff cement and pouring melted sulphur, into which sand has been irred, about the ball. Another method of insulator support is to use heavy rthenware truncated cones in place of the sulphur piers.

114. The strength of electrolyte at full charge in stationary types batteries is usually limited to 1.200 to 1.215 sp. gr., and a sufficient volume electrolyte is usually present in the cells so that its strength does not ll below 1.150 to 1.160 sp. gr. at the end of discharge.

115. Typical charge and dis-harge curves of Planté station-y-type cells are shown in Fig. 26. he upper charge curve is for the nor-al or 8-hr. rate, subsequent to a com-ete discharge at the same rate. The ain part of the charge curve is similar plates of different standard make



IG. 26.—Charge and discharge curves.

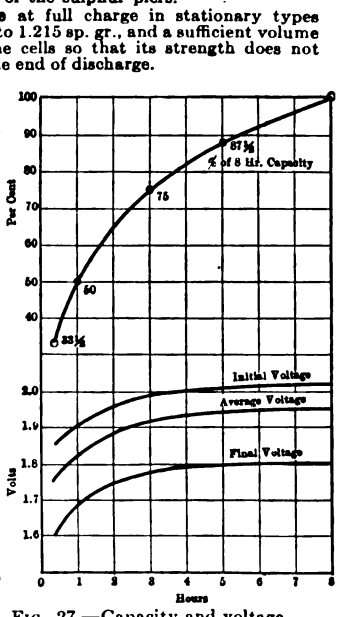


FIG. 27.—Capacity and voltage characteristics.

design, but the latter part of the curve will show wide variations with te design and age of plates. The factor which seems to be of greatest portance in determining the maximum voltage value reached on charge

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is the condition of the negative plates with reference to a possible deposit of impurities on their surfaces. The maximum value reached with continued charge at the normal rate may be as high as 2.65 volts with the cell at 70 deg. Fahr., and as low as 2.45 volts. All commercial lead contains a small percentage of impurities such as copper, antimony, etc., and these are eventually deposited from the positives, with their proceeding corrosion, onto the negative-plate surfaces. The result of these deposits is generally to reduce the final charge voltage. If a positive-plate grid contains antimony, the effect is quite marked. Antimony, artificially introduced into a cell, will produce this effect.

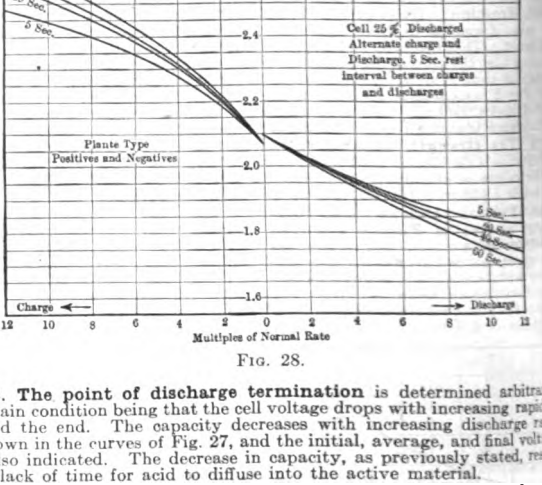


FIG. 28.

116. The point of discharge termination is determined arbitrarily, the main condition being that the cell voltage drops with increasing rapidity toward the end. The capacity decreases with increasing discharge rate, as shown in the curves of Fig. 27, and the initial, average, and final voltages are also indicated. The decrease in capacity, as previously stated, results from lack of time for acid to diffuse into the active material.

117. Voltage variations on intermittent charges and discharges. Stationary types of lead batteries are capable of charging and discharging at high rates for short intervals, with a relatively small variation of voltage. The curves of Fig. 28 show voltages at the end of charge and discharge for the times indicated on the different curves. These curves are of importance in determining the variation of line voltage with a "floating battery," or that amount of work necessary to be done by a booster generator in series with a battery, in order to maintain a constant line voltage.

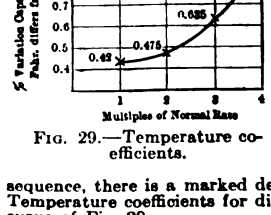


FIG. 29.—Temperature coefficients.

118. Variation of capacity with temperature. The rate of diffusion of acid into the pores of the plates varies markedly with temperature, and, in consequence, there is a marked decrease in capacity with lower temperatures. Temperature coefficients for different rates of discharge are as shown in the curve of Fig. 29.

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19. Nominal battery ratings. Frequently a stationary battery is erred to as having a kilowatt-hour capacity. By this is meant the 8-hr. normal ampere-hour capacity multiplied by the number of cells and by open-circuit voltage per cell, which is approximately 2.1 volts.

ELECTRIC VEHICLE BATTERIES

20. Adaptable types. Pasted plates are universally used in vehicle teries at the present time, although there is no reason why a battery h Planté positives and pasted negatives should not be successful on ac- nt of its greater ability to withstand "boosting" charges. By a sting charge is meant a partial charge at a high current rate, such a charge ing place at the noon hour or other rest period after the battery is partly charged. The Planté positive, even with a pasted negative, may be rged at enormously high rates without the injurious heating which elops in the Edison battery.

f in a particular service the ability of a battery to withstand boosting igh rates is of importance, this combination should receive consideration. The prime reason for the use of pasted plates is their relative lightness, e a reduction in weight of battery results in a reduced current consump- n for the vehicle and a reduction in the expense of tire upkeep. For these sons, battery-plate life is often deliberately sacrificed by using thin plates l a small separation between plates. Small separation makes it necessary employ strong acid and this reduces the life of the separators as well as life of the plates. There is a strong tendency toward the use of thicker arators and a reduced acid strength

21. Plate dimensions. The size of plate in general use for vehicle pur- es is 5¼ in. × 8¼ in. Standard positive plates vary from 0.22 in. to 0.13 in thickness, negative plates from 0.19 in. to 0.11 in. Several other s of plates are occasionally used, but they are gradually being abandoned.



FIG. 30.—Vehicle plate grid "shelf type."

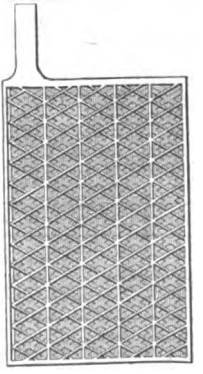


FIG. 31.—Vehicle plate grid "diamond type."

Negatives are usually made thinner than the positives with which they are ed by several hundredths of an inch, so that the plates of each polarity ll have approximately equal life. Each battery manufacturer makes eral thicknesses of plates, the proper thickness to use under any condition ng dependent on the ampere-hour capacity required and the space and ight limitations. In a definite size of jar, a greater capacity can be ob- ned with a larger number of thin plates at high discharge rates. The cost the thin-plate battery in the same size jar is somewhat greater, and the

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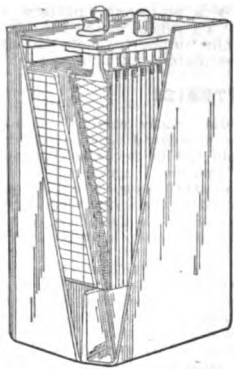


FIG. 32.—Vehicle cell construction.

ampere-hour life is slightly less. The ratios obtained from bench tests, under exaggerated charging conditions, are shown in Par. 125.

122. Choice of plate thickness. In the examples cited in Par. 125, the prices and, also, the "probable life" are to be considered as comparative. The ratios hold for several makes of battery. Where maximum mileage radius of a vehicle is necessary, the thinner plates should be chosen. The best all-round results will be obtained, in the judgment of many, from using the intermediate plate thicknesses.

123. Grid types. The only two grid designs in general use with the ordinary plate are those illustrated in Figs. 30 and 31.

124. Vehicle battery construction is illustrated in Fig. 32. Jars are universally of hard rubber. Celluloid is not suitable for vehicle batteries on account of its inflammability. It also oxidises in contact with positive plates and becomes worthless. The bottoms of jars contain supporting ribs or bridges upon which the plates rest; these bridges provide a space beneath the plates to take up sediment which is gradually thrown off from the plates in service.

125. Relative Attributes of Plates of Different Thicknesses

Size of plates 5 in. × 8½ in. Size of jars 6¼ in. wide × 4¼ in. long

Type of plate	Weight per cell (lb.)	Capacity at 6-hr. disch. rate (amp.-hr.)	Approximate price to user (dollars)†	Average life (amp.-hr.)
Thick (heavy duty)..	36.8	150	11.00	75,150
Medium (standard)..	34.0	170	11.70	75,300
Thin (high capacity).	34.5	190	12.10	75,400
Extra thin (extra high capacity).....	35.8	200	12.75	67,200
Iron clad*.....	34.5	170	16.75	170,000

Size of plates 5½ in. × 8½ in. Size of jars 6¼ in. wide × 8⅛ in. long

Type of plate	Weight per cell (lb.)	Capacity at 6-hr. rate (amp.-hr.)	Approximate price to user (dollars)†	Average life (amp.-hr.)
Thick (heavy duty)..	70.0	305	19.50	155,000
Medium (standard)..	65.0	341	20.75	150,000
Thin (high capacity).	65.9	384	21.20	153,000
Extra thin (extra high capacity).....	64.0	420	22.30	141,000
Iron clad*.....	65.0	340	30.45	340,000

126. Separators. The plates are insulated from each other by thin sheets of corrugated wood veneer, grooved on one side, the wood used being either naturally free from such organic substances as would injure the plates or else treated to remove such impurities. These veneers are usually kept away from the positive plate by inserting a thin sheet of perforated hard

* See Par. 75. †The excise tax is not included.

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rubber. The smooth side of the veneer is placed against the negative plate. The life of these wood separators is unfavorably influenced by very strong acid also by an excessive amount of overcharge. If batteries are properly operated, the separators will last as long as will the plates of a thin-plate battery, that is, 12 to 15 months in commercial service and 18 to 24 months in pleasure-vehicle service.

Thick plates will generally have a longer life than the wood separators, so that, in order to obtain the best possible life of the plates, the separators will require renewal. If the separators and the plates are to give approximately equal lives, sufficient space should be provided in the jars to take all the sediment which will be thrown off in the life of the plates, *i.e.*, high-bridge jars should be used. Otherwise the space should be ample to take the sediment which will be deposited during the interval between separator renewals.

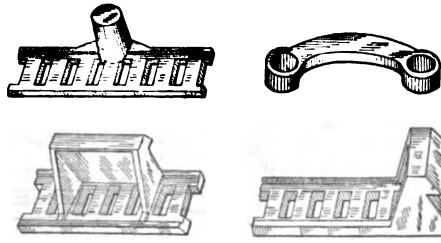


FIG. 33.—Vehicle type straps and connector.

127. The straps to which the plates are burned are of several types, as shown in Fig. 33. The pillar-post strap, used with connector links, is generally considered to be the best design. Several kinds of bolted connections are on the market, but most of them are unsatisfactory. A burned connection is preferable.

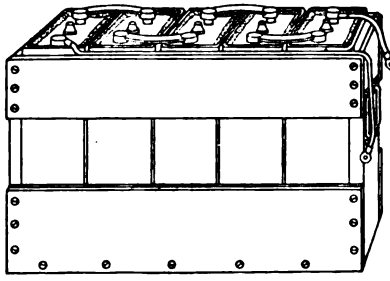


FIG. 34.—Vehicle battery assembly.

128. Covers. The cells are preferably provided with covers of hard rubber, sealed with an acid-resisting compound, to prevent slopping of the electrolyte, although frequently a tight-fitting cover is relied upon to prevent this. If the covers are sealed, **vent caps** of either hard or soft rubber are used.

129. Degrees of separation of plates. As it is desirable to reduce weight and space required, as far as possible, with vehicle batteries, separation between plates and the volume of electrolyte are limited; on this account the range of acid strength between the states of full-charge and full discharge is great. In extreme cases, acid of 1.300 sp. gr. at full charge is used, and only sufficient volume employed to give a final acid density of 1.100. A better life of plates and separators will result, however, if a wide enough separation between plates is used to permit a full-charge density of 1.260 to 1.280 sp. gr.

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130. Crates. The method of assembling vehicle cells into crates is shown in Fig. 34. The crates are of hard wood, painted thoroughly with asphaltum acid-resisting paint or else soaked in hot paraffin oil, then subsequently dipped into melted paraffin. The practice of fastening crate terminals onto the crates is to be thoroughly condemned, as when the crates become acid-

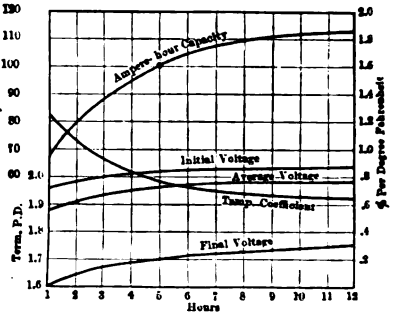


FIG. 35.—Capacity voltage and temperature characteristics.

soaked, there is current leakage between them, and the positive terminal corrodes seriously. Crate ends are charred from this cause, and the current leakage is of a magnitude not to be neglected.

131. Performance of thin-plate batteries. The variation of capacity of a thin-plate vehicle-type battery in wide commercial use, is shown in

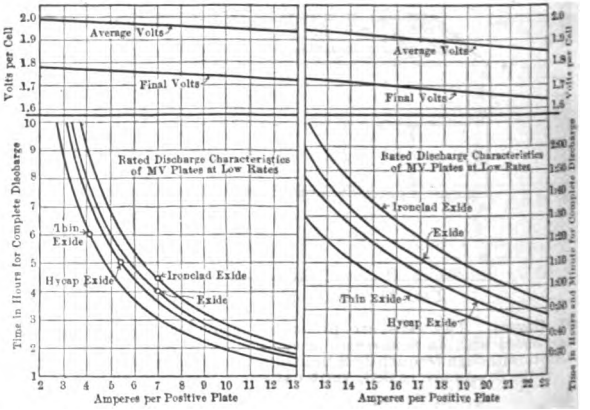


FIG. 36.—Exide plate characteristics.

Fig. 35, and the average and final voltages are also given. The Electric Storage Battery Co. has devised an ingenious chart showing the characteristics of their "Exide" batteries which is reproduced in Fig. 36.

TRAIN-LIGHTING BATTERIES

132. Capacity. A special type of battery has been developed for the lighting of steam railroad trains. The standard battery comprises 16 cells

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of 300 amp -hr. rated capacity, and this size is used in most cases for coaches, parlor cars, and sleeping cars. For dining cars, 32 cells are frequently used. Batteries of smaller capacity are often used for lighting baggage and postal cars.

133. These batteries are charged either from an outside source at terminal yards, or, especially where the cars run over several different lines, are operated in conjunction with an automatically controlled axle-driven generator. The "head end system," with a steam-driven generator in the baggage car is sometimes used, though it is not so popular as formerly. (See Railway Train Lighting, Sec. 22.)

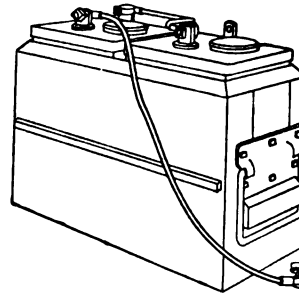


FIG. 37.—Train-lighting battery.

134. Design. Batteries for train lighting have been standardized. The cells are mounted in pairs in double-compartment wooden tanks, with lead linings. The tanks are provided with insulating porcelain rollers or skids on the bottom; also with insulating side and end buffers of porcelain or paraffined wood. The covers are sealed in with a suitable asphaltum compound, the covers being of lead-antimony or hard rubber. Soft-rubber bushings are used around the terminal posts where they emerge from the covers, in order to absorb the shock incidental to the service.

The tank linings are embedded in an asphaltum compound of relatively low-melting point (about 135 deg. fahr.) the compound completely surrounding the lining on the sides and bottom. This construction prevents electrolysis of the linings to a large extent. The plates are supported on porcelain rests held in lead channels burned to the bottom of the tank linings. In the construction now used by the Electric Storage Battery Company the lead-alloy linings are replaced by jars of a tough rubber compound (Standard Giant Compound) which are held in place in the two-compartment crate by paraffined wooden shims or spacers. The jars are provided with double lead-antimony covers sealed with asphaltum compound. The plates rest on supporting ribs or bridges moulded in the bottoms of the jars. It is claimed that the use of the rubber-compound jars does away with trouble from electrolysis.

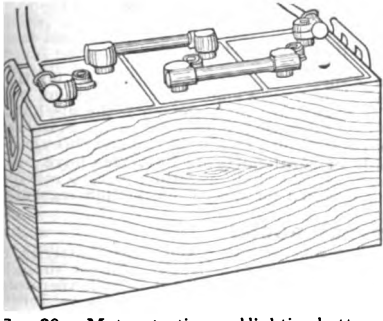


FIG. 38.—Motor starting and lighting battery.

The elements usually comprise Planté plates, both positive and negative, although pasted plates are sometimes used. With Planté plates, the separators are perforated hard-rubber sheets with marginal ribs about ¼ in. wide on each side, and also are provided with narrow intermediate ribs, inclined slightly to the vertical in opposite directions, on each side of the sheet.

135. Life of train-lighting batteries. These batteries if properly cared for, will have a life of from 4 to 8 or 9 years, dependent somewhat on the amount of discharge to which they are subjected. They are usually opened up for inspection 2 years after first being placed in service, and subsequently once a year. Any sediment accumulation is then removed and the plates are straightened, if this be required.

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136. Voltage characteristics of train-lighting batteries are practically the same as for cells of the stationary type (see Par. 115).

BATTERIES FOR MISCELLANEOUS PURPOSES

137. Automobile starting, lighting and ignition batteries. Batteries for this service have been specially designed to meet the large current demands required for engine starting. Normal voltages of 6 and 12 volts are usual, although there are a number of 16-, 18- and 24-volt systems. The lower voltages are preferable on account of the better durability of the low-voltage lamps. (See "Electric Equipment for Gas Automobiles," Sec. 22.)

The battery elements are made up of a large number of thin plates, usually with thin corrugated wooden veneer separators, and without perforated hard-rubber sheets, the latter being omitted to reduce the voltage drop on the very high discharge rates for starting. The initial current value is frequently three times the rated ampere-hour capacity of the battery, and, in order to reduce the voltage drop, cell connectors and terminals have copper cores. Plate grids are also usually provided with reinforcing diagonal members for the same purpose. Fig. 38 shows a standard battery design for motor starting and lighting.

138. The voltage characteristics of these batteries, as furnished by several manufacturers, are shown in Fig. 39.

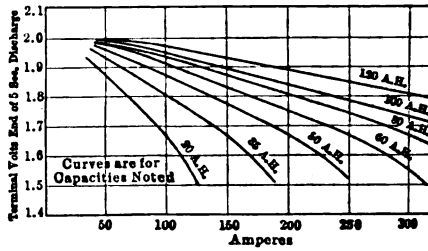


FIG. 39.—Motor starting battery characteristics.

139. Batteries for ignition alone. The current required for ignition rarely exceeds an average value of from ½ to 1 amp. For this reason, batteries for ignition alone usually have thick plate elements, the discharge rates being so low that the full plate thickness is efficiently used. Standard batteries for this service are for 4 and 6 volts, that is, of two and three cells.

140. Other types of portable or semi-portable batteries have been developed for many purposes such as: oil-switch operation, wireless service, etc. Manufacturers should be consulted for special information regarding these.

BATTERY ROOMS

141. General rules. It is desirable to install stationary batteries in rooms which have good ventilation and are well lighted. Direct sunlight should not, however, be permitted to fall on the cells; it is well, therefore, to coat windows with an opalescent paint, in order to avoid this possibility and also to cause the illumination of the entire room to be more equally diffused. Where natural illumination is not possible or convenient, a liberal number of electric lamps should be provided. Open flames and fires in stoves must not be permitted, as the cells give off hydrogen and oxygen on overcharge and the mixture of these gases, if sufficiently concentrated, is explosive.

142. Temperature. A battery room should be maintained at as nearly 70 deg. Fahr. as possible. Higher temperatures than 95 deg. to 100 deg., excepting during rare intervals, must be avoided. Low temperatures temporarily reduce the battery capacity, but do no injury.

143. Cleanliness of location. Batteries should not be installed adjacent to an ice plant, or to a stable, as ammonia gas is absorbed with great

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avidity by the electrolyte, and eventually crystals of ammonium sulphate collecting on the containing tank may cause the electrolyte to syphon off by capillary action. The capacity of negative plates is reduced by the presence of ammonia. Corrosive gases or vapors from other manufacturing processes should also be avoided. Iron ore dust is also objectionable.

144. Ventilation. If large batteries are to be installed in the immediate vicinity of dwellings, forced ventilation may have to be provided, during the completion of charge, by means of an exhaust fan. The acid vapors may be removed from the exhaust by sucking it through several layers of bronze screen or thin perforated sheets of lead. Exhaust ventilation is much preferable to direct, as air currents are more uniform and there are fewer eddies. The acid spray in the first method does not so readily precipitate upon the tanks and insulators.

145. Protection to iron work and walls. There should be a minimum of exposed piping and iron work in a battery room, especially near the floor. If radiators or coils are present, they should be as high from the floor as possible and kept painted with asphaltum paint. At the floor level and for the first 4 or 5 ft., it is especially desirable that the iron work be protected. On ceilings and on walls above the top level of the cells, a good white-lead, linseed-oil paint should be used. The white walls and ceiling will materially assist in the illumination of the room.

146. The floor of a battery room should receive particular consideration, especially if, as frequently occurs in large cities, a large battery is erected in an upper story of a building containing iron or steelwork in its floor. A good floor specification in this case is the following: A layer of concrete is spread over the floor, the surface being "floated"—not trowelled. This surface is thoroughly mopped with hot "Hydrex" compound (a pure grade of Trihidad asphaltum) and a layer of "Hydrex" felt is then laid, the edges being flashed on the walls and other uprights about 3 in. Three layers of this felt are laid, the surface of each being thoroughly mopped with hot Hydrex compound. Care must also be taken that the abutting joints of the sheets of one layer do not match with those of the lower layer. Two-inch tile, of a grade which is not porous and which is not attacked by acid, are then laid, a space of $\frac{1}{2}$ in. being left between the tile. Hot Hydrex compound is then poured in these spaces. The floor should be pitched toward drains, the pitch being at least $\frac{1}{8}$ in. per ft. The drains should have a sheet-lead catch basin, all joints in which should be lead-burned, and lead pipe should be used for the drains. Covers to drains should be of bronze, which withstands sulphuric acid to a satisfactory degree for this purpose. Such a floor construction is quite expensive and is only warranted for the conditions above stated.

If a battery is installed on a ground floor and the room can be kept fairly dry, a concrete floor will be quite satisfactory. The floor must, however, be flushed at frequent intervals and acid must not be slopped on the floor. Any leaky cells must be promptly repaired and the spilled acid promptly neutralized with washing soda. A concrete floor can be protected to a satisfactory degree (in the absence of ironwork in its construction) by mopping with very hot paraffin, applied with a heavy brush to prevent too rapid cooling. In those cases where an expensive construction is not warranted fair results can be obtained by keeping sawdust on the floor to absorb the acid spray from overcharge or any spilled acid.

147. Arrangement of wiring. Conductors to terminals and between rows of large batteries should be of bare copper, supported on glass insulators and horizontal runs should be at least 4 ft. above the tops of the cells. The copper should be liberally smeared with vaseline. Lead-covered copper cable makes a very good conductor for running in a battery room. Rubber-covered cable, without braid, is also satisfactory if the rubber covering is high grade.

148. Location of switchboard. Switchboards and end-cell switches should not be installed in a battery room on account of the presence of acid-containing vapors given off during charge. It is well to provide a separate room for these parts.

149. General layout. In laying out a battery room, liberal aisle spaces should be provided if possible. There should be at least 6 in. space between walls and a row of cells. With glass-jar installations, 30-in. aisles are satis-

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factory for passage ways, and, if the battery is installed in double rows, there should be a clear space of at least 4 and preferably 6 in. between adjacent rows. With lead-lined tank installations, sufficient aisle space must be provided to remove tanks, if necessary, by up-ending.

REGULATING EQUIPMENT

150. Voltage regulation. Since the voltage of a battery falls on discharge and rises on charge, it is necessary to compensate for these variations in some way, if a constant line voltage is to be maintained. With small batteries on steady charge or discharge, regulation for constant voltage is sometimes effected by means of an adjustable resistance in series with the battery, the battery either being split in two halves in parallel for charge or a shunt charging booster used to add sufficiently to the line voltage in order to charge the cells in a single series. Another method of voltage regulation sometimes used is to absorb the excess voltage at the beginning of discharge by means of "counter-e.m.f. cells" (Par. 151). With large batteries, the losses of the preceding methods are avoided by the use of automatic regulating boosters (Par. 153) or end cells with end-cell switches (Par. 161).

151. Counter-e.m.f. cells. These are simply cells with unformed plates. When current flows through such cells, they oppose the main battery voltage by approximately 2.8 volts for each counter-e.m.f. cell in series. They are so connected in a circuit that current always flows through them in the same direction, as otherwise they would gradually attain a considerable capacity. End cells are no more efficient than resistance for controlling voltage, but they possess the distinct advantage of giving a voltage drop which does not vary greatly with the current. All the energy absorbed in such cells is used in electrolyzing the water they contain. For this reason the frequent addition of water is necessary.

152. Shunt charging booster. This consists of a generator, usually motor-driven, whose field is excited from the line; actually, therefore, the designation is misleading. A variable resistance in series with the field permits the adjustment of the booster voltage to the desired value. These boosters are connected as shown in Figs. 47 and 48.

153. Automatic regulating booster. The charge and discharge of a battery may be made responsive to variations of any desired magnitude by placing a motor-driven generator in series with the battery, the field of the generator being excited in accordance with such variations. Automatic boosters usually regulate for constant current or for constant voltage. Current regulation is the more frequent application. Regulating boosters are usually driven at practically constant speed. They are used when rapid variations of battery charge and discharge are required.

154. Ents booster. Mailloux proposed the use of two opposing field coils on the booster generator, one a shunt coil excited from the line voltage, the other carrying the total current. The Ehtz modification of this scheme, formerly in wide use, is shown in Fig. 40, in which the coil *A* carries the current from the generator, *B* carries the load current, while the shunt coil *C*, excited at line voltage, carries a practically constant current opposed to *A* and *B*. The coils are so determined that the resultant booster field is zero when both the outside load and the generator load have a certain definite value. Any increase in the outside load then causes a resultant field, and consequently a resultant booster voltage, in the direction forcing the battery to discharge. Any portion of the increased load falling on the generator would tend still further to increase the booster field and result in additional battery discharge. The resultant booster voltage would be in the opposite direction if the outside load decreased and the battery would be forced to charge. Regulation tending to produce constant generator cur-

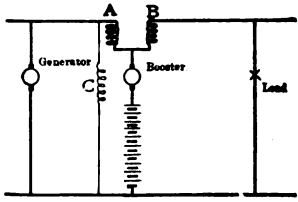


Fig. 40.—Entz booster.

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ent, therefore, results from this scheme. A practical defect of the Entz ooster is that the field structure must carry much more than the normal mount of winding and a highly special machine results.

155. Separately-excited booster. The modern boosters have fields of ormal dimensions with a single winding excited from a separate machine for his purpose. The excitation schemes in practical use are of two types escribed below.

156. Carbon-pile regulator. This regulator is shown diagrammatically n Fig. 41 in which two piles of carbon discs are under but a slight ompression when the lever arm is in the horizontal position. The ever arm is operated by a solenoid plunger whose coil carries the current to be regulated. The pull of the solenoid is balanced by a spring whose tension is such as to equal the solenoid for normal average current. The bottoms of the two piles are connected, one to the positive and the ther to the negative of the battery, and the two tops of the piles connected ogether. One terminal of the booster field is connected to the junction of he two piles, the other to the middle point of the battery. With the two piles nder equal compression, no current flows through the booster field. An ncrease of current from the main generator causes the solenoid to compress ne of the carbon piles and release the pressure on the other; in consequence f the reduction of resistance of the carbon piles under pressure, current lows from the middle point of the battery through the booster field and the ile under greater compression, the current being in the direction which will ause the battery to discharge. A reduction of the main generator current auses the field to reverse and the battery to charge. The regulator is adjusted for various average values of main generator current simply by changing the spring tension. The amount of current that can be handled by the carbon piles is limited, so that, for large boosters, the carbon-pile regulator acts as the field control of an exciter for the booster generator. These regulators are supplied by the Electric Storage Battery Co.

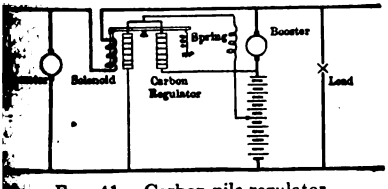


FIG. 41.—Carbon-pile regulator.

157. Counter-E.M.F. booster regulator. This scheme is due to A. S. Hubbard and is furnished by the Gould Storage Battery Co. Referring to Fig. 42, the main booster field is across the line, but there is an exciter machine, E, included in the field circuit. The latter is usually mounted upon the same shaft with the main booster set and its field is either the whole or shunted portion of the main generator current. When the current in the field of the exciter machine has its normal average value, the exciter machine is designed to give the full line voltage and in this case zero voltage is applied to the main

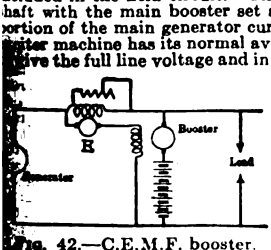


FIG. 42.—C.E.M.F. booster.

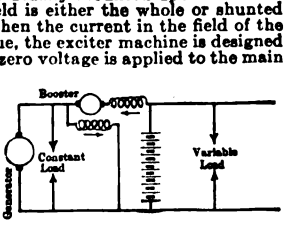


FIG. 43.—Constant current booster.

booster field. With a reduction in value of the main generator current and consequently in the field of the exciter machine, the voltage of the latter is reduced, so that current flows in the main booster field in a direction causing the battery to receive charge. If the main generator current increases above the average value, the voltage of the exciter machine is in excess of the line voltage and current flows in the booster field coil in a direction causing the

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battery to discharge. Shunting any portion of the current from the field of the exciter machine increases the main generator current; for example, a shunt across the exciter-machine field of equal carrying capacity and resistance means that the value of the main generator current must be twice as great in order that the exciter-machine voltage may be equal to the line voltage (the point at which the battery will neither charge or discharge). Adjustment for any desired average generator load is made by variable shunts on the exciter field.

158. Differential booster. When boosters are connected as shown in the two preceding diagrams, they are designated as differential boosters as distinguished from those of the succeeding paragraph.

159. Constant current boosters. In many instances, a portion of the plant load, such as that of incandescent lamps, requires steady voltage, while the remaining load is satisfactorily supplied at a voltage which may vary by, say, plus or minus 10 per cent. from the generator voltage. In this event, the booster capacity can be reduced, under certain conditions as explained below, by connecting it in circuit as shown in Fig. 43 where the constant-load circuits such as for lamps, motors, etc., have an electrical position between the main generator and the booster, and the variable load circuits, such as result from hoists, elevator operation, etc., are taken off the opposite side of the booster and are subjected to the battery voltage variation. If the average value of the variable load is less than the difference between the maximum load and the average load, it may be possible to reduce greatly the booster capacity by so connecting it as to realize constant generator current.

160. Electrical position of booster regulator. Where a portion of the station load is steady and another portion variable, the regulating coil should in general be so placed as to be affected by the variable load only, if this is conveniently possible. This can be done by grouping the constant and the variable loads separately, the coil then being placed between the two groups of loads. The position indicated will result in closer regulation, since all the practical regulating schemes provide that the current to be regulated shall not depart from its average value by more than a given percentage. This rule holds for both constant-current and differential boosters.

161. End-cell switches. An end-cell switch is a device for cutting in or cutting out cells of a series and thereby compensating for battery voltage variation. The contacts of the smaller size switches are usually arranged in the arc of a circle, while with larger sizes the contacts are arranged in a straight row and a heavy laminated copper brush is moved over these contacts by means of a motor-driven worm. In switching from one point to the next, the circuit must not be opened, and the blade must not touch two adjacent contact points, as this would short-circuit a cell having its terminals connected to these points. End-cell switches are therefore provided with an auxiliary contact, either on the moving blade as shown in *B*, Fig. 44, or, in some instances, fixed adjacent to each main contact. The main and auxiliary contacts are joined by a resistance as shown at *C*, but otherwise insulated from each other. The auxiliary contact touches one of the switch points, while the main contact touches the adjacent point. The circuit is, therefore, not interrupted, being completed through the resistance, *C*, which has too low a value to affect the line voltage appreciably. Its resistance, however, is sufficiently great to prevent short-circuiting the cells connected across the two points. The larger sizes of end-cell switches are motor-driven, and are very elaborately designed. The reader is referred to the literature of the various manufacturing companies for full particulars of these switches.

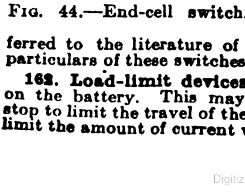


FIG. 44.—End-cell switch.

162. Load-limit devices. It is sometimes desirable to limit the load on the battery. This may be accomplished by providing an adjustable stop to limit the travel of the lever arm of the carbon-pile regulator, and thus limit the amount of current which will flow through the booster field. This

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turn, will limit the amount of battery charge and discharge. An equivalent device for the same purpose can be applied to the Hubbard booster.

163. Average adjuster. It is often desirable to limit the work which a battery does, to taking simply those heavy variations of current which persist for short times, and to allow the main generator to follow the load averaged over relatively long intervals. A device which accomplishes this object is furnished by the Electric Storage Battery Co., and its design is dependent upon the following principle: the armature of a small motor is connected to the adjusting screw which controls the tension of the spring of the carbon pile regulator, through a suitable train of reducing gears. The armature of this motor carries a practically constant current, as it is connected across the line in series with a fixed resistance. The field of the motor is connected across the terminals of the booster. The effect of this arrangement is to permit the battery to absorb momentary fluctuations, while the main generator current follows the load averaged over a relatively longer interval.

OPERATING EQUIPMENT

164. Pilot cells. The specific gravity of the electrolyte of a cell in which the acid level is kept constant by adding water to replace evaporation, is the best means of determining the state of charge of a battery. One or two cells of a battery should be selected for this purpose; these will be known as "pilot cells," and records should be kept of their acid density. With stationary batteries, an automatic cell filler should be provided and maintained. In other cases, the evaporation should be replaced daily, preferably before starting the charge.

165. Auxiliary operating apparatus. To follow the operation of a battery the following apparatus should be available: (a) **low-reading voltmeter,** with a scale of +0.3 to −3.0 volts, with **"stabbers"** (to make contact with the cell terminals). (b) **Cadmium test electrode,** comprising a cadmium rod covered with perforated rubber. This is suitably combined with this previously mentioned "stabbers" and is used to determine the relative condition of the positives and negatives. (c) **Examination lamps;** these are bulbs at the ends of flat hard-rubber or glass tubes so that they may be inserted between plates in lead-lined tanks. The lamps are for low voltage (2 or 3 cells), and enable the interior at the cell to be examined. (d) **Compensating hydrometer;** either an hydrometer which automatically compensates for temperature differences should be supplied or a thermometer should be kept in the pilot cell and the hydrometer readings corrected for temperature. Many consider the latter course preferable. (e) **Ampere-hour meters;** these instruments are frequently used to determine the state of charge of a battery, but they should be checked from time to time with the acid readings of the pilot cells. An ampere-hour meter will not determine the amount of local action which takes place in a battery. It is usually assumed that a certain percentage of overcharge will be required to take care of this.

STORAGE-BATTERY APPLICATIONS

166. Applicability of stationary types. The characteristics of batteries which make them essentially valuable with reference to their practical application in power plant work are, (a) they do not contain moving parts and are capable instantaneously of furnishing current; and, (b) they will absorb and give out current at high rates and at high efficiencies. Because of their voltage variation on charge and discharge, auxiliary apparatus (Par. **150** to **163**) must be used if the line voltage is to be maintained constant.

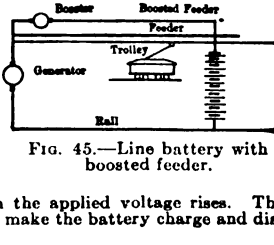


FIG. 45.—Line battery with boosted feeder.

167. Line or floating batteries. If a battery is connected directly across a line whose voltage varies, then the battery will discharge when the applied voltage is reduced below its open-circuit or floating voltage, and it will charge when the applied voltage rises. The amount of voltage variation necessary to make the battery charge and dis-

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charge at various rates may be determined from the curves, Fig. 28. A battery of the stationary type will neither charge at appreciable rate unless the voltage exceeds 2.14 volts per cell, nor discharge unless the voltage is below 2.04 volts per cell. A battery may therefore be practically floated at any voltage per cell between the limits just stated, although the value 2.08 volts per cell is usually taken as the best point. If a number of cells equal to the average voltage, divided by 2.08, are placed across a line, therefore, the voltage variations will be limited to those of the battery when charging and discharging at the rates necessary to furnish the current demand. The capacity of the battery is determined from the condition that frequent discharges should not exceed twice the 1-hr. rate and frequent charges should not exceed the 1-hr. rate.

Battery installations of this nature may be installed at points distant from a power source, in order to maintain a more constant line voltage under heavy fluctuating loads such as may result from the operation of cars on interurban railways or unloading machines at docks, etc., etc. Batteries may also be floated directly across the terminals of heavily under-compounded generators.

168. Railway line batteries with boosted feeder. The voltage at the distant ends of long lines with infrequent service, can be satisfactorily maintained by connecting a battery as shown in Fig. 45. The feeder can be tapped into the trolley at a short distance from the battery in the direction of the power-house. It is necessary to provide a reverse-current circuit-breaker in circuit with the generator.

169. Load-regulating batteries. Batteries may be installed to absorb momentary fluctuations above or below the average load, or any desired percentage of these fluctuations. In this connection it is usual practice to employ an automatic regulating booster (Par. 163) to force the battery to charge and discharge in accordance with the load variations. The number of cells usually installed is equal to the line voltage divided by 2.08, and the size of the battery is generally determined by the condition that frequently recurring discharges shall not exceed twice the 1-hr. discharge rate of the battery. Under these conditions, the main battery voltage will not fall below 1.6 volts per cell nor exceed 2.6 volts per cell under regular operating conditions. To maintain the line voltage at maximum rates of battery discharge, the booster, for regulating service, should therefore have a voltage range equal to approximately 0.48 volt times the number of cells. A limiting voltage of 2.65 volts per cell must, however, be available to complete the regular charge of the battery and to give it the necessary overcharge it occasionally must receive. Provision must be made either by increasing the speed of the booster, or else by forcing the booster field to reach the extreme voltage (for booster and generator together) of 2.65 volts per cell in order to give the battery its periodic overcharge. Fig. 46 is a diagram of connections, showing how batteries are applied for this purpose. Regulating battery plants are installed in connection with generators, motor-generator sets or rotary converters, supplying railroad, rolling-mill, elevator and other widely varying loads.

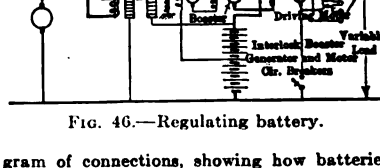


FIG. 46.—Regulating battery.

170. Alternating-current regulation. If there is a reversible means of converting alternating to direct current on an alternating-current source of supply, and it is desired to equalize the load variations on the latter, the battery may be made to do this by exciting the booster field in accordance with these variations. The lever of the carbon-pile regulator (Par. 185) would then be subjected to a pull in proportion to the load in watts or to the power component of the load. A solenoid coil carrying the current only will not effect the desired result unless the power-factor remains constant.

Another method of securing equalisation of alternating-current variations is to rectify the secondary current from series transformers in the line and

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ch a way that the output of the rectifier is proportional to the power mponent of the load. The latter may then be used to excite the c.e.m.f. citer of the Hubbard booster. The literature of the Gould and Electric orage Battery Companies should be consulted for details of this method.

171. Peak-load batteries. If a battery is to supply a discharge of atively long duration and at constant voltage, it is usual to effect the ltage regulation by means of an end-cell switch. A diagram of connec- ns for a direct-current two-wire system is shown in Fig. 47. The arging booster is employed for the purpose of adding to the line voltage sufficient amount to complete the charge of all the cells of the battery. ants of this nature are used supply hotel and residence hting and motor circuits, it are infrequently used for gular operation with large ants, except for emergency serve.

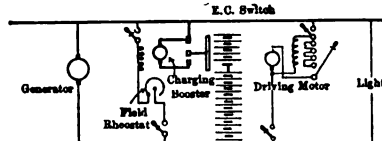


FIG. 47.—Peak-load battery.

172. Isolated-plant batteries in hotels and office buildings. Batteries with eans for appropriate regu- tion are quite frequently stalled in connection with ie generating apparatus in such buildings, for the purpose of eliminating ie voltage variations which would result from variable elevator loads and order to reduce the capacity requirements of the generating equipment. many instances the battery is also called upon to furnish energy during ie night, when the generators are shut down. The battery capacity will e determined by that requirement which preponderates, whether it be the omentary discharge capacity for regulating or the continuous discharge apacity when carrying all the load after the generators are shut down. he booster is usually of the constant-current type, and end cells are added the battery to maintain the proper voltage on continued discharge when ie generator is not in operation. The elevator circuits may be taken off ie main portion of the battery, inside the end cells; the booster, however, so connected that the end cells are in its circuit, through the end-cell witch, until these end cells are charged.

173. Batteries for exciter and oil-switch reserve. It is important, large plants, that current be always available for the operation of oil witches and, temporarily, for excitation to prevent a shut-down, or in start- g up. Battery current is frequently provided for oil-switch operation and lso for excitation when it is of advantage to start quickly after a shut-down. oil switches only are to be provided for, the vehicle type of battery will offer the cheapest and most convenient means for the purpose. A separate battery room is not then necessary. The diagram of connections for an exciter and oil-switch battery is the same as that of Fig. 47.

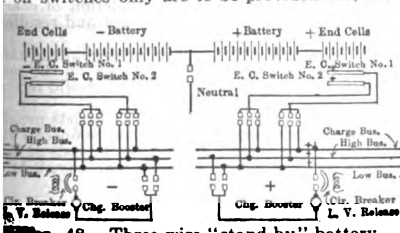


FIG. 48.—Three-wire "stand-by" battery.

174. Stand-by batteries. Batteries to insure continuous power supply on direct-current three-wire networks are in wide use in the most important cities of the country. In fact, it may be said that one of the advantages of the direct-current three-wire distribution is that storage batteries may be floated on such a distribution, so that, in case of an interruption of the power supply, the voltage is still maintained on the network and the annoyances and dangers of light failure in theatres and crowded streets are eliminated. The general practice of applying such batteries is illustrated in Fig. 48. On a three-wire system with a minimum bus pressure of 230 volts maintained between the

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outside wires, it is usual to float a battery of 150 cells between the outside wires, that is, 75 cells on each side of the system. Connection to the proper cell, to insure that the battery neither charges nor discharges, when "floating," and to regulate the voltage on discharge, is effected by means of end-cell switches. It is usual to connect cells No. 55 to 59 inclusive, on both the positive and negative sides of the system, to the end-cell switches, while the balance of the cells are connected, first in groups of two and then in groups of three, to the remaining points of the end-cell switch. The first single-cell intervals are provided so that the battery may float without charge or discharge under the usual range of bus-pressure variation. The remaining intervals of two and three cells make it possible to reduce the heavy copper runs which would be necessary with single-cell intervals.

A shunt charging booster is usually employed for charging stand-by batteries, and, during the charge, the battery, in standard practice, is not immediately available for emergency discharge, except in the reverse direction through the booster. However, the battery is always charged at times of relatively light load when there is little danger of disturbance to the system, also, when a momentary failure would not be of vital importance.

It is usual practice to install two end-cell switches on each side of the battery and this permits floating the battery simultaneously across the high and low buses. The possibility of doing this is not usually taken advantage of in regular operating practice, and the end-cell switches are usually installed in pairs for the sake of limiting the amount of current to be carried by a single contact. Provision is not made in the majority of cases for floating the battery on the buses during charge, for the reason that a greater number of end-cell points would be required, and because of the heavy expense of the copper runs to the additional number of end cells. The capacity of a battery for stand-by service is frequently determined by the requirement that it shall carry the maximum station peak for a period of 5 or 6 min., and that the usual 150 cells shall maintain a voltage of about 115 volts per cell during this period. Although the life in ampere-hours discharge of cells with pasted-type plates is less than that of cells with Planté plates, the life of such cells in standby service may be as great, due to the infrequency of their discharge. For a given capacity they occupy much less floor space and cost much less.

175. Batteries for telephone exchanges. The batteries of the large offices are either 11-cell or 22-cell installations, and are floated directly across the power circuit without any special regulating means. The capacity of these batteries is usually such that they will carry the entire station load for a period of 24 hr. or longer. The internal resistance of the batteries is extremely low, owing to the relatively large size of the cell used. A low internal battery resistance is especially desirable for telephone service, in order to eliminate the possiblity of "cross talk" (Sec. 21). It is desirable with these batteries, to select a type that will permit completion of charge at a relatively low rate in order to avoid excessive voltages and resultant interference with relay operation and lamp signals.

Planté type cells are usually used for the purpose on account of their long life. Pure-lead Planté negative plates show high voltages on the completion of overcharge, especially when new, and this fact should receive consideration.

The loads on telephone-office power plants in business districts usually show decided morning and afternoon peaks, and it is usual to operate the charging generator in parallel with the battery during the periods of high load. The battery alone usually carries the load except from, say, 9 A.M. to 4 P.M. in the typical exchange in business districts.

176. Residence and farm lighting plants. A great number of these plants are in service, and they vary in elaboration from a simple battery without voltage regulation (the battery being taken off the lighting service when charging) to the more complete plants previously described. The usual low-voltage plants have 8 and 16 cells and are for 15 and 30 volt lamps. The small plants frequently use vehicle or motor starting and lighting batteries, as these are cheaper for the same capacity and may be readily shipped to a service station for repairs when necessary. The couple types (Par. 108) of stationary batteries are also frequently used. The regular stationary types will give longer and somewhat more reliable service. Diagrams of connection are given in Figs. 49 and 50. With the former there

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is no voltage regulation, while with the latter voltage regulation is effected by counter-e.m.f. cells.

177. Electric-vehicle battery applications. The use of vehicle batteries in electric-truck service is fully covered in Sec. 17. Additional applications are covered in Par. **178–180.**

178. Storage-battery street cars. The field for the battery car is limited to those cases where the traffic is not great enough to justify electrification in the ordinary manner, or where for special reasons the overhead trolley is not permissible. In a number of smaller towns or cities storage-battery cars are operated because the investment for equipment is much less than it would be for the regular overhead trolley, and the expense of continuous power-plant operation under poor load conditions is thus avoided. In these cases the batteries are charged from the local power service between midnight and early morning, that is, at a time when the stations are willing to supply the energy at a moderate charge. The majority of battery cars now in service, have 18-ft. bodies and are 28 ft. long over-all. They seat 28 passengers and their weight, fully-equipped, is approximately 14,000 lb. The battery equipment comprises 58 cells of approximately 385 **amp.-hr.** rated

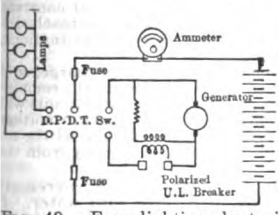


FIG. 49.—Farm lighting plant without voltage regulation.

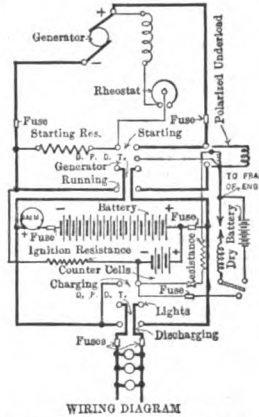


FIG. 50.—Lighting plant with voltage regulation.

capacity, and the current consumption varies from 5 to 6 amp.-hr. per car-mile. The cars are capable of making in daily operation 75 to 100 miles or more on a single charge of the battery. The success of the modern storage-battery car is due to the use of light-weight cars with high-efficiency ball-bearing motors and axles.

179. Storage-battery locomotives. These are employed in shops for handling heavy castings, moving freight cars through short distances, etc., and also in tunnel excavations and for gathering cars in coal mines. Such are wide and growing applications for storage batteries.

180. Freight and baggage-handling trucks. The larger passenger terminals have placed a great many of these trucks in service for handling baggage, express and mail. The standard truck for this purpose is capable of carrying about 4,000 lb., and its maximum speed is limited to 4 or 5 miles per hr. A 12-cell battery of 195 amp-hr. capacity is the one most usually employed for this service. A number of these trucks are also in operation on steamship piers and in freight warehouses. Smaller trucks are widely used in manufacturing plants, for the transfer of work from one department to another.

OPERATION

181. Operation. In order to obtain satisfactory battery life, a few simple instructions should be carefully followed. It is frequent practice for the battery manufacturer to guarantee his battery, and, in this event, he will not, of course, accept responsibility for damage to the battery unless his operating

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instructions are followed. The characteristics of plates as furnished by the different manufacturers vary somewhat, and therefore any special instructions given by the manufacturer should take precedence. The following general rules should be followed:

182. Batteries should not be overdischarged, and after the completion of a discharge they should be recharged within a reasonable time.

183. Determining the charge of a battery should be differentiated as follows: (a) the completion of regular charge; (b) the completion of overcharge (Par. **184**). The determination of completion of regular charge is that all cells are gassing uniformly, both from positives and negatives; that with the current maintained at a constant value there is no further increase of voltage as determined by successive 15-min. readings; that the acid density corrected for temperature is within 0.003 sp. gr. of the maximum reached on the last preceding overcharge. It is good practice to maintain one or two pilot cells (Par. **184**) in the battery and to use the acid readings of these cells as determining the state of charge of the whole battery. Batteries which are operated in this way will show a slight formation of sulphate in the plates, and this, for a limited time, is not injurious but beneficial. If the sulphate formation is allowed to continue indefinitely, large insoluble crystals of lead sulphate are formed, and the plates will become *injuriously sulphated.*

184. To reduce fully or oxidize the sulphate, the battery should receive a periodic overcharge at intervals of at least once a week if the battery is called on for heavy service, or once every 2 weeks if the service is light. The overcharge is simply a continuation of the regular charge until the battery voltage at constant current input has remained constant and also until the acid density, corrected for temperature, has reached a maximum value as indicated by three successive acid-density determinations at half-hourly intervals, having the same value.

If any cell or cells are late in gassing or become warm during charge, or if the specific gravity of the electrolyte is markedly lower than in the remaining cells, they should be investigated for short-circuits. Short-circuits will also be made evident if any cell falls materially behind the others in voltage on discharge. An excessive amount of charge should be avoided, as the resultant gassing will throw off some of the active material, especially from the positive plates.

185. Removal of separators. If for any reason it is necessary to remove wood separators from a cell, they should be kept covered with water. If allowed to dry out they will shrink, and the resulting concentration of acid in the wood will ruin them. Wood separators which have been in acid for several months will have so little strength that they cannot be handled without danger of breaking. New separators should be kept damp to prevent their shrinkage.

186. Evaporation of the electrolyte should be replaced by adding pure water. Keep the level of the electrolyte well above the tops of the plates. Do not add acid to the electrolyte unless it is clearly established that the removal of possible short-circuits and the subsequent overcharges will not restore the density of the electrolyte. Both water and electrolyte should be pure. It is preferable to add water before an overcharge, as the gassing will serve thoroughly to stir up the acid and equalize any differences in specific gravity between the tops and bottoms of the cells.

187. Operating temperatures. It is best not to allow the temperature of a battery to exceed 100 deg. Fahr.; a temperature above 105 deg. should positively be avoided.

188. It is well to note the color of the plates from time to time and to see that the color of the plates in different cells is uniform.

189. If the battery is low in capacity, the relative condition of the positive and negative plates should be determined by taking voltage readings between both the positive and negative groups and a cadmium test electrode. This should be done toward the end of the discharge and will determine which of the groups are at fault.

190. If any cell shows low voltage or low acid-density by reason of short-circuits, it should be separately charged after the short-circuits have been removed. In large installations a **milker set** is usually provided for this purpose. This comprises a motor-generator supplying energy at from

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3 to 6 volts. Another method is to cut out the cell on discharge and replace it in the series on charge.

191. The strength of the acid to be used in various types of cells should be that prescribed by the manufacturer. It will depend entirely upon the battery design. The usual practice is to use electrolyte of 1.210 sp. gr. with stationary types of cells, while with vehicle types and with motor-starting and lighting batteries, maximum densities of 1.300 sp. gr. are sometimes used. The higher density will give a greater capacity but it will shorten the life of a cell in which it is used. In tropical or warm climates somewhat lower densities should be employed.

192. Be sure that sediment does not accumulate to such an extent as to touch the bottoms of the plates, as this would cause internal short-circuits in the cells. Separators must be kept in place and in good order. The entire battery should be kept clean and free from dirt. Condensed moisture or acid vapors should be wiped off from time to time, and the insulation kept dry. Raw linseed oil should be applied to the wood of lead-lined tanks as occasion demands.

193. Charging rates. The recommendations of the various manufacturers differ widely as to the proper charging current values. The following is general practice, although the manufacturer of the battery should always be consulted on this point.

With Planté positive plates having centre webs, it is desirable to start the charge of the battery at as high as the 3-hr. rate, and to finish the charge at not less than the 8-hr. rate. Tudor-type positives may be charged at lower current rates than these, but at not less than one-half the preceding values. Batteries with Manchester-type positive plates should not be allowed to gas when charged at a rate above the normal 8-hr. charging rate, and an excessive amount of gassing should be positively avoided.

With pasted-plate batteries, best results will be obtained by charging at low rates. With stationary types, the charge should be started at about the 3-hr normal rate and finished at one-half this value. With pasted-type vehicle batteries, the charge may begin at as high as 6 amp. per positive plate, but the completion of charge should be carried out at not more than 2 amp. per positive plate. These values hold for the standard size of plates, (5¼ by 8¼ in.) and should be varied in proportion to the plate area for other sizes. As the cells begin to gas on charge, the charging current should be reduced to the minimum values just given.

The constant-potential method of charge wherein a battery is connected, without resistance, directly across a charging source having a voltage maintained at a value equal to the number of cells multiplied by 2.3, is advocated by many operators of vehicle batteries. This method insures a rapid charge of a battery without either gassing or overheating. For this method the line voltage, if too high, can be reduced by inserting counter e.m.f. cells in series with the battery, each counter e.m.f. cell reducing the voltage by approximately 3 volts. In applying this method, the literature of the battery manufacturers should be consulted. The constant-potential method of charge is particularly adapted for the "boosting" of batteries.

194. Fires, or flames must not be permitted in battery rooms, unless the rooms are well ventilated; they must especially be prohibited when cells are gassing. Never bring a flame near a sealed-type cell.

195. The usual troubles to which a storage battery is subjected result either from overcharge or undercharge, or from allowing short-circuits to occur in cells. If the trouble has not been of too long duration, in practically all cases the battery can be brought into good condition by proper charge, presuming that, with the short-circuited cells, the shorts first have been removed and the separators put in good condition. Planté-plate batteries which have become sulphated should have their remedial charge started at about twice the 8-hr. or normal rate, which is to be reduced to normal when vigorous gassing ensues. Any of the methods of "rejuvenating" battery plates should not be carried out without having obtained the advice of the battery manufacturer or a qualified storage-battery expert. The methods which have been proposed for charging the battery in electrolyte containing sodium, potassium or magnesium sulphate, are to be condemned as impracticable, excepting on an experimental scale.

196. The initial or developing charge should be very carefully carried out in accordance with the directions of the manufacturer of the battery.

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Practice varies considerably in this regard, and the manufacturer will not accept responsibility for injury to the battery if his directions have not been followed. Points which should receive consideration are the following:

(a) Be sure that the positive pole of the battery is connected to the positive pole of the charging source.

(b) Always, in pouring electrolyte into cells containing dry plates, there is a certain amount of chemical reaction between the acid and the plates, especially the negatives. If the electrolyte becomes warm, it is well to allow sufficient time, before starting the initial charge, for the cells to cool down. A few hours, also, are required for the absorption of electrolyte by the pores of the plate.

(c) With Planté-plate batteries, the current at beginning of charge should be well above the normal rate, and should be reduced to the normal rate when vigorous gassing takes place at the positive. With pasted plates lower rates are employed.

(d) If the cells reach a temperature of from 103 to 105 deg. Fahr., the charging current must be interrupted and the cells allowed to cool. If it is found necessary thus to interrupt the charging current, the number of ampere-hours of initial charge must be increased.

(e) The initial or developing charge is to be considered complete only when both positives and negatives are gassing uniformly in all the cells, and when there has been no increase in voltage or specific gravity of electrolyte (the latter corrected for temperature) for a period of 5 or 6 hr. The battery should then be open-circuited for an hour or so and, subsequently, the current applied again; in this charge, the cells should begin to gas from both positives and negatives within a minute or two.

(f) The battery should not be allowed to discharge until it has been fully developed as above. The color of the positives should be a very deep brown, and the negatives a light lead color.

197. Placing batteries out of commission. If a battery is not to be used for several months it should receive a very thorough charge before allowing it to stand idle. It is desirable, though not absolutely necessary, to give it a freshening charge of an hour or so once a month. If glass-jar batteries are to be left over winter and low temperatures will be met, it may be necessary to remove the acid, see Par. **93.**

If a battery is to remain out of service an indefinitely long time, it will be advisable to remove the acid. Before doing this, it should be given a thorough overcharge. If the plates are to remain in the cells, syphon off the acid and remove the wood separators. Watch cells carefully and when the negatives become hot sprinkle with water. If the plates are to be removed from the cells, keep the positives apart and simply let them dry out. Do not rinse in water. The negative plates must be carefully kept apart, and sprinkled with water as soon as they become hot.

DEPRECIATION AND MAINTENANCE OF LEAD STORAGE BATTERIES

STATIONARY BATTERIES

198. General considerations. As with generating machinery, obsolescence, due principally to changes in service requirements, is the important factor in depreciation. A stationary battery may be maintained indefinitely by replacing worn-out parts, but a renewal of tanks or the replacement of a battery-room floor is a considerable item of expense. In these events it will frequently be advisable to reconsider the entire installation. Many floating batteries on interurban lines have given ten to twelve years of service with a single renewal of positive plates. The same result has often been obtained with regulating batteries.

199. Actual maintenance costs. A case of five large railway regulating batteries which are called upon daily, excepting Sundays, for peak discharges each morning and afternoon, the ampere-hours of discharge aggregating approximately the equivalent of one 8-hr. discharge per day may be cited. A blanket contract to furnish and install all the maintenance material required to maintain the five batteries in efficient operating condition for a second term of 10 years was entered into, the contractor undertaking to do this for approximately 8 per cent. per annum of the initial cost

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f the installation. The foregoing are among the hardest-worked batteries nstalled in the United States. Stand-by batteries can be maintained for a eriod of 10 to 15 years at from 3 to 4 per cent. per annum of the cost of nstallation.

200. Life of plates. Planté positive plates in regulating or line batteries rill have lives of from 7 to 12 or more years if they are in hard service, and hould last longer in light service. Planté negative plates should outlast wo sets of positives within a period of 12 to 14 years. Box negatives (74) hould have a longer life, probably 20 years, if used with pure lead Planté ositives. Paste positives in stand-by service show every indication of eing good for 15 years of service, negatives being good for a somewhat onger period. The scrap lead of plates, to be replaced, has a considerable alue and the cost of plate replacements should be credited with this value. lanufacturers will usually guarantee a minimum life of plates if they know he service conditions.

201. Life of tanks. Glass jars are good until broken, and a few jars, specially in the larger sizes, will break from time to time outside of ccidental causes. This breakage is usually a consequence of imperfect nnealing of such jars, and should not aggregate more than 5 to 7 per cent f the total number. The life of lead-lined tanks will depend on the care rith which the insulation is maintained, and on whether the wood is kept rotected from acid. The chief cause of the depreciation of tanks is pitting f the lead linings by electrolysis. Tanks should last 20 years or more prorided they are kept covered, gassing due to excessive overchargeis prevented, hey are occasionally oiled or painted, and the insulators are kept clean.

202. Acid and water. These are small items and properly come under he head of operating expense.

203. Wooden separators. Wooden separators of poplar have a life of rom 2 to 5 years, depending largely on the amount of gassing to which a attery is subjected from overcharge. They rapidly lose their strength after nstallation, but if it is not necessary to disturb them when removing plates or straightening or for other causes, they will act as efficient diaphragms or the number of gears mentioned above.

204. Other parts. Glass covers will be broken from time to time; the umber will depend entirely on the care of the attendant. Glass support lates will be broken occasionally but the number should be small. Busbars nd copper should not require renewal during the life of the battery. Wooden and trays will require renewal at intervals depending on the care with hich they are kept dry and free from acid when filling cells with water.

205. Sediment removal. Modern practice is to install tanks with a iberal space below the plates for sediment accumulation. The cost of leaning between intervals of plate renewals is great enough to warrent the light extra cost of a battery installation when such space is provided. The njury to the battery insulation and battery-room floor from slopping of cid is another justification for deep tanks.

VEHICLE BATTERIES

206. General considerations. Batteries in pleasure vehicles, on account f the limited use to which they are subjected, frequently last 2 to 3 ears. Batteries in truck service should last at least 1 year if of the thinlate type and longer with thicker plates.

207. Life of plates. Thin-plate batteries of the better makes in commercial service should give 12 to 15 months of service. Thick-plate atteries should have a plate life of 16 to 24 months, the vehicle supposedly n operation each week day. Batteries with iron-clad plates (see Par. 75) hould have a life of 2½ to 3 years. Plate life will be increased by avoiding overcharge especially at high rates, also by employing as wide a plate separaion as possible to avoid the necessity of strong acid. Edison type A atteries should have a life of about 5 years.

208. Life of wooden separators. If the acid strength is not excessive nd overcharge is avoided, wood separators should last during the life of the lates. With thick-plate batteries it may in some cases be necessary to eplace them once.

209. Life of jars and hard-rubber sheets. The compound of the sual jar and perforated sheet is not rich in rubber, and its constituents

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harden with age. They become especially brittle if the battery is permitted to overheat on charge. Unless jars are of good material a large number will be broken when plates are renewed.

210. Life of other parts. Battery crates usually require renewal when the plates wear out. If the crates are kept dry however they will frequently be in good enough condition to warrant their use with a new set of plates. Negative crate terminals will in most cases be intact but the positive terminals if not kept well covered with vaseline will require renewal when plates are replaced. Hard-rubber covers for cells will usually be in good condition, but a few will be broken in removing sealing compound. Soft-rubber vent plugs depreciate considerably, but these are quite inexpensive. Cell connectors and straps have a high scrap value and it will usually be cheaper to replace old vent plugs by new ones when overhauling a cell.

TRAIN-LIGHTING BATTERIES

211. Effect of overcharge. The maintenance of train-lighting batteries has varied widely under different operating conditions. Some of the earlier batteries were serviceable for 9 or 10 years with negligible replacements. The best results have been obtained with batteries which were not overcharged. Overcharging requires the frequent addition of water and if this is not done carefully the insulation of the tanks is injured. Overcharge also results in a greater deposition of sediment from the positive plates and shortens the life of the battery. The present tendency is to design axle-lighting equipments to maintain practically constant-voltage charging conditions. Constant-voltage charging causes little gasing and results in a longer life of the batteries.

212. Frequency of cleaning. Train-lighting batteries which are properly charged can be kept in operating condition for 3 years without being opened up for cleaning. After cleaning the first time such batteries should be cleaned at intervals of 2 years. With many railroads the practice is to make the first cleaning 2 years after placing in service, with subsequent intervals of 1 year between cleanings.

ALKALINE STORAGE BATTERIES

213. Classification. There are but two practical types of alkaline storage batteries in commercial use: one is the Hubbell, used in the miners' lamps of the Portable Electric Safety Light Co.; the other is the Edison storage battery.

214. The Hubbell battery differs from the Edison in principle only in using a negative plate of cadmium instead of the iron of the Edison battery. Hubbell apparently was the first to use nickel threads incorporated in the nickel-oxide active material, and this is one of the essential steps in the production of a practicable battery plate with this active material. The nickel oxide of the original Edison battery contained flake graphite to increase the conductivity; the graphite was seriously affected by electrolyte action, and these plates were short-lived. In the present type of Edison battery flake nickel replaces the graphite of the earlier type. In December, 1914, the first few of these batteries had completed 5 years of service.

215. Theory of the Edison battery. The active materials of the Edison battery consist of nickel peroxide for the positive plate and finely divided iron for the negative plate. The electrolyte is a 21 per cent. solution of potassium hydrate in water to which is added a small amount of lithium hydrate. To overcome the passivity of iron a certain amount of mercury is incorporated with the iron of the negative plate; a suitable compound is also incorporated with the nickel hydrate which is the salt from which the nickel peroxide is electrolytically formed. The nickel oxide is a relatively poor electrical conductor, and, for this reason, layers of flake nickel are added to the mass to increase its conductivity. The theory given by the Edison Storage Battery Company for the chief chemical reactions which take place in their cell after the first charge is:

$$3Fe + 8OH = Fe_3O_4 + 4H_2O \qquad \text{(Negative Plate)} \quad (11$$

$$6NiO_2 + 8K + 4H_2O = 2Ni_2O_4 + 8KOH \qquad \text{(Positive Plate)} \quad (12$$

$$8KOH + 6NiO_2 + 3Fe + 4H_2O = Fe_3O_4 + 2Ni_2O_4 + 4H_2O + 8KOH \quad \text{(Both Plates}$$

$$6NiO_2 + 3Fe \underset{\leftarrow \text{charge}}{\overset{\text{discharge}\rightarrow}{}} Fe_3O_4 + 2Ni_2O_4 \qquad (13$$

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A probably more correct theory is given by Dr. Fritz Foerster, Elektrochemie Wasseriger Losungen, p. 227, 1915, as follows:

$$\text{e} + Ni_2O_3 \cdot 1.2H_2O + 1.8H_2O \underset{\leftarrow \text{charge}}{\overset{\text{discharge}\rightarrow}{}} Fe(OH)_2 + 2Ni(OH)_2 \text{ (Both Plates)} \quad (14)$$

NiO_2 is first formed on charge but decomposes into the lower oxide, Ni_2O_3, ·cording to the equation, $4NiO_2 = 2Ni_2O_3 + O_2$, giving off oxygen. This ·composition accounts for the continual gasing which takes place during ıarge and also for a considerable length of time after the charging is dis-ɔntinued. If a cell is allowed to stand idle after charge, it will take om 1 to 2 days for the higher oxide to completely decompose to Ni_2O_3. his reduction is much hastened by discharge since any NiO_2 existing in ıe positive plate will be used up first. This rapid reduction on discharge any NiO_2 which may be present probably accounts for the marked drop voltage at the beginning of the discharge of a freshly charged cell. Due) the presence of the higher oxide in the positive plate of a freshly charged ·ll, the voltage of such a cell is somewhat higher than the voltage of one ıat has been allowed to stand before discharge.

Foerster's equation shows that, although the potassium does not enter ıto the chemical reactions, the water of the electrolyte does and that there ı an increase in the density of the electrolyte from the charged to discharged tate. This change is opposite to the change which takes place in the dens-y of the electrolyte of the ordinary lead accumulator. Although there is a ecrease in the density of the electrolyte of an Edison cell during charge, his change cannot be used to determine the state of charge of the cell on ccount of the uncertainty of the amount of water lost by gasing during harge.



FIG. 51.—Edison positive plate.

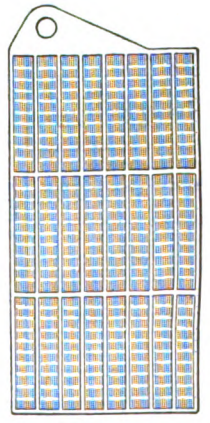


FIG. 52.—Edison negative plate.

216. Positive-plate construction. The positive plate consists of a ıickel-plated steel frame into which are pressed perforated tubes filled with ılternate layers of nickel hydrate and metallic nickel in very thin flakes. The tube is formed from a thin sheet of steel, nickel plated and perforated, ınd has a spirally lapped joint. The active material is tamped into the tubes, ıickel hydrate and nickel flake being fed alternately and the tubes when ılled have their ends pressed together in such a way to permit them to be ıounted in the frames. The tubes have small steel bands slipped over them o prevent expansion away from the active material. Such a plate is shown ı Fig. 51.

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217. Data on Edison Cells

Type of cell	B–2	B–4	B–6	A–4	A–5	A–6	A–8	A–10	A–12
No. positive plates	2	4	6	4	5	6	8	10	12
No. negative plates	3	5	7	5	6	7	9	11	13
Weight (lb. per cell) without trays	4.7	7.5	10.8	13.9	16.7	19.4	27.2	33.3	41.3
Capacity (amp.-hr.)	37.5	75	112.5	150	187.5	225	300	375	450
Charge amp. for 7 hr.	7.5	15	22.5	30	37.5	45	60	75	90
Discharge amp. for 5 hr.	7.5	15	22.5	30	37.5	45	60	75	90
Avg. volts per cell discharged at above rate	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2
Amp.-hr. efficiency	82	82	82	82	82	82	82	82	82
Watt-hr. efficiency	60	60	60	60	60	60	60	60	60
Watt-hr. per lb. of cell without trays	9.6	12.0	12.5	13.0	13.5	13.9	13.2	13.5	13.1

218. Negative-plate construction. The negative plate comprises a grid of nickeled steel with oblong openings into which are placed perforated steel boxes or pockets containing finely divided iron with mercury. See Fig. 52. These

FIG. 53.—Edison cell construction.

boxes are assembled in the grid and subjected to pressure to weld the joints and to corrugate their surfaces. The iron is precipitated with a chemical compound, and the nickel hydrate and

FIG. 54.—Crate mounting.

this iron compound are converted electrolytically to nickel peroxide and metallic iron respectively, in the forming of plates.

219. The assembly of the cell is shown in Fig. 53. The plates are supported on hard-

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ber spacing and insulating pieces. The lugs of the plates are punched and e mounted upon a steel pin with a terminal post. The ends of the pins e threaded and the plates, separated by washers, are held together by el nuts. The elements are contained in a nickel-plated sheet-steel case, e walls of which are corrugated to add stiffness and also to assist in cool- g the cells in action. The cover also is of nickel-plated sheet steel with ee openings, two for the terminal bushings, which are provided with ffing boxes, and the third for the gas vent and for the filling of the cell th water.

The cells are assembled in wooden crates as shown in Fig. 54, usually th the bottom left open to secure a circulation of air sufficient to keep e cells cool.

The normal rates of charge and discharge for Edison cells with A- and type plates are respectively 7 and 5 hours. The G-type plates are thinner an the A and B types and are for higher discharge rates. Cells of ap- oximately the same dimensions with A- and G-type plates have the same mpere-hour capacity, but for a fixed voltage drop on discharge those with e G-type plates may be discharged at the higher rate. The normal rates charge and discharge forlcells with G-type plates are respectively 4½ and hours.

The numerals following the type designations in Table 214 indicate the mber of positive plates. Each type-A positive plate has 30 tubes ¼ in. diameter and is capable of giving 7.5 amp. for 5 hr. The type-B sitive plates have half as many ¼-in. tubes and give 3.75 amp. for 5 hr. lls with A-type plates are standard for electric commercial vehicles, ucks, locomotives, etc.

220. Charge and discharge curves. The characteristic normal charge d discharge curves for an Edison battery are given in Fig. 55. It will be ted that the average voltage on discharge is approximately 1.2 volts; the itial open-circuit voltage is approximately 1.5 volts, and the final voltage the end of discharge is approximately 1 volt. The first part of charge ows a characteristic voltage rise, and there is a subsequent decrease in ltage with continued charge, followed by another rise. There is no ex- emely sharp rise in the final voltage of the Edison cell, and it is therefore mewhat difficult to determine the end of charge. If an Edison cell is

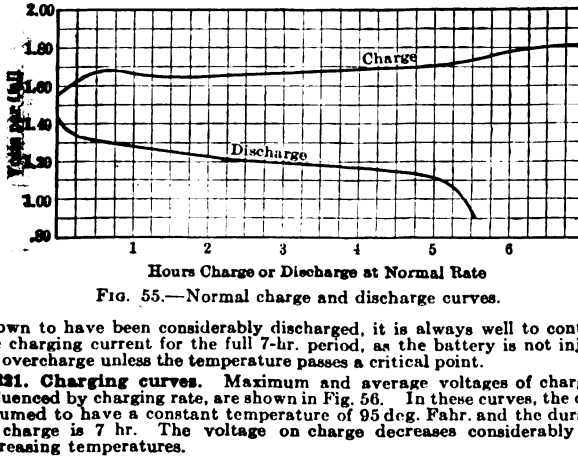


FIG. 55.—Normal charge and discharge curves.

own to have been considerably discharged, it is always well to continue e charging current for the full 7-hr. period, as the battery is not injured y overcharge unless the temperature passes a critical point.

221. Charging curves. Maximum and average voltages of charge as fluenced by charging rate, are shown in Fig. 56. In these curves, the cell is sumed to have a constant temperature of 95 deg. Fahr. and the duration charge is 7 hr. The voltage on charge decreases considerably with creasing temperatures.

222. Characteristic discharge curves. Characteristic discharge urves for Edison type "*A*" cells are given in Fig. 57. It will be noted

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that the ampere-hour capacity of an Edison cell does not suffer very greatly from increasing discharge rates, if the terminal voltage be carried low enough. For practical purposes, however, the last portion of the discharge at high rates would have no value because of its great falling off from the open-circuit voltage.

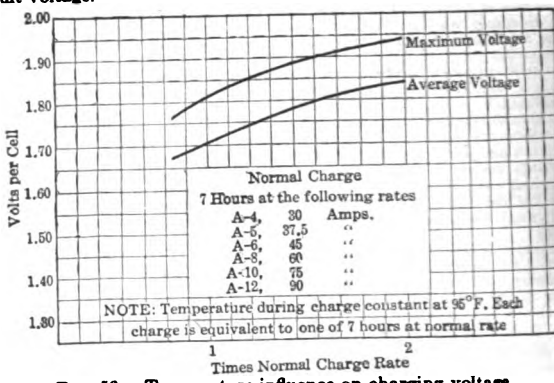


FIG. 56.—Temperature influence on charging voltage.

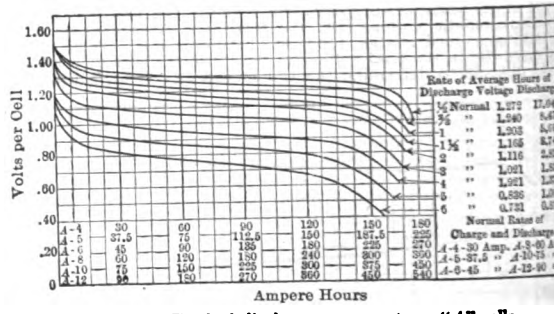


FIG. 57.—Typical discharge curves, type "*A*" cells.

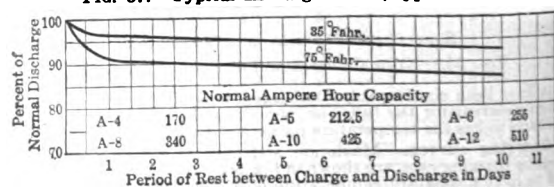


FIG. 58.—Loss of capacity.

223. Standing discharged. No injury is done to the Edison cell if it is completely discharged and allowed to stand in this condition. This is one of the principal distinguishing features of the Edison cell. The cell

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owever, loses in capacity by standing as shown in Fig. 58, and is most ıaily brought back to its condition of full capacity by giving it a very con-derable overcharge. The usual practice is to ship the Edison battery in discharged condition, and it requires several cycles of charge and discharge) bring it to its full capacity.

224. Overcharge. The Edison battery is not injured by overcharging nless its temperature exceeds 105 to 110 deg. Fahr. High temperatures ıriously affect the capacity and life of Edison negative plates, and the ıanufacturer's guarantee does not hold for overheating from this cause. continuance of overcharge increases the capacity on the subsequent ischarge, but this increase in capacity is obtained at the expense of efficiency. he effect of continued overcharge is shown in Fig. 59.

225. Effect of temperature. There is a marked falling off in capacity f the Edison battery with low temperature, especially at high discharge ıtes. There appears to be a fairly well defined temperature for any given ischarge rate below which the capacity becomes quite suddenly reduced. See W. E. Holland, Elec. Vehicle Assoc., Oct. 10, 1911.) For this reason he battery compartments of electric vehicles using Edison cells must be arefully insulated against cold, if low temperatures are to be met. If the ıattery has attained a low temperature from long standing, it will tend to eat up on discharge, because of the high internal resistance, and if this heat ı retained by the insulation, a fairly complete discharge can be obtained.

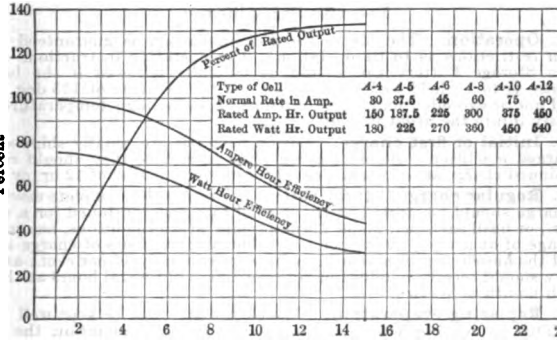


FIG. 59.—Influence of overcharge.

226. Deterioration of electrolyte. Water must be frequently added to ıe electrolyte of an Edison battery, to replace that lost by decomposition ıd evaporation. The amount of water required for this purpose is con-derably greater than with a lead battery, because of the poor ampere-hour fficiency (due principally to the continuous gassing during charge) and the ıgher temperatures reached on charge. Distilled water must be used for ıis purpose, but even with its use, the electrolyte becomes gradually con-erted to potassium carbonate through the absorption of carbon dioxide om the air. For this reason also, it is preferable to use water which has een freshly distilled. As the electrolyte deteriorates from the above-ıentioned cause, the capacity of the battery falls off, and, after about 50 cycles of charge and discharge, the electrolyte should be renewed. fter each electrolyte renewal there is a temporary increase in capacity as ıown in Fig. 60.

227. Testing. Tests on Edison batteries should be carried out as ıscribed in Par. **103** to **107**, with certain obvious changes. There is no ıpreciable variation of electrolyte density, and the end point of charge is so determined with greater difficulty than with the lead battery. A

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suitable neutral or test electrolyte for an Edison battery is a nickel-oxide tube, such as those used in the standard positive plates.

228. Application. The "*B*" type cells are used for ignition and lighting of gasoline motor cars; they are not commercially used for motor starting on account of the high internal resistance. The vehicle-type cells are used for electric vehicle propulsion, storage battery street cars, mining locomotives and industrial trucks; they are not used for load regulation on account of the heavy drop in voltage at high discharge rates and the high initial cost, these factors also limiting their use in other power applications.

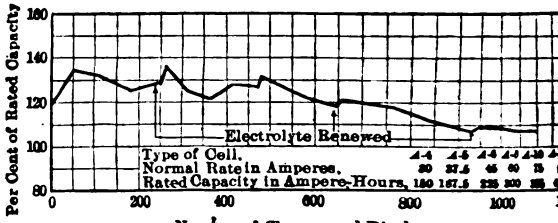


FIG. 60.—Log of life test.

229. Operation. The life of the Edison battery is guaranteed under certain restrictions as to its operation. The operating instructions of the Edison Storage Battery Co. should be carefully followed if the battery company is to be held to its guarantee. A temperature of 115 deg Fah. should not be exceeded under any circumstances, as high temperatures will seriously injure the negative plates.

230. Initial or first charge. Edison batteries are usually shipped in a discharged condition. Before placing them in service they should receive a continued charge at the normal or 5-hr. rate, for a period of 12 hr. or more.

231. Regular charge. If the battery has received a complete discharge, the charge should be started at the normal rate and continued for a period of 7 hr., or until each cell, under normal temperature conditions, has reached a voltage of at least 1.8 volts per cell. The ampere-hours of charge should exceed the ampere-hours of discharge by approximately 40 per cent., and the battery should receive in addition, an overcharge of several hours at the end of each month of service.

232. Replacing evaporation. The electrolyte must be kept well above the plates by adding water whenever necessary, to maintain the level. Always use distilled water for this purpose.

233. The outside of the cells and the trays must be kept clean and dry. Dampness under certain conditions will cause the containers to pit under electrolytic action.

234. Standing idle. If an Edison battery is to be placed out of commission it need not receive any special attention, other than to see that the electrolyte is brought to the proper level. The battery can stand either charged or discharged equally well. To obtain the full capacity, however, after a long period of standing it is necessary to overcharge the battery.

235. Life of Edison battery. A log of a life test as published by the Edison Storage Battery Co. is shown in Fig. 60. The statement is made that the conditions of the test were harder than would normally be met in service. The battery is more durable than the vehicle type of lead battery. It is doubtful if it approaches the durability of the heavy Planté type of lead cells.

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SECTION 21

TELEPHONY, TELEGRAPHY AND RADIOTELEGRAPHY

BY

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SECTION 21

TELEPHONY AND TELEGRAPHY

BY

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DEFINITIONS

1. **The scope of this section** is confined to the needs of electrical engineers who encounter telephone or telegraph problems only in the sense of an adjunct to a major operation, or subsidiary to the main work in hand. Therefore the section deals exclusively with those applications of telephony and telegraphy which may be termed **private-line systems**, as found in connection with steam and electric railways, transmission and distribution systems, industrial plants, etc.

2. **Telephone systems** may be classified, according to their commercial uses, as follows:

Telephone Systems { *Public* { *Exchange*, *Toll* }; *Private* }

3. **Public telephone systems** are those operated for commercial profit under some fixed schedule of tariffs or rates. Such systems must serve all who apply, and are usually subject to some form of regulation as to rates and service by the public authorities. Any public system might be broadly defined as a common carrier of intelligence or communication.

4. **Telegraph systems** may be classified, according to their uses, as follows:

Telegraph Systems { *Public*, *Fire Alarm*, *Police*, *Private* }

5. **Public telegraph systems** may be defined in general the same as public telephone systems, in Par. 3, with the exception that the mode of communication of course is different.

6. **Private telephone and telegraph systems** are those operated as auxiliaries to some other form of business or enterprise (Par. 1), but not directly for commercial profit. Private systems are sometimes interconnected with public systems, and in other cases are completely isolated. Any private system which is operated under especially hazardous conditions, such as long parallel exposure under a high-tension transmission line or close proximity to a single-phase traction system, should be connected to a public system, if at all, only through efficient protective apparatus designed to reduce to an absolute minimum the probability that dangerous potentials or currents will penetrate beyond the protection to any part of the public system.

7. **Private systems may be classified**, according to their uses, as follows:

Private Systems { *Train Dispatching*, *Load Dispatching*, *Line Patrol*, *General communication*, *Intercommunicating* }

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hing systems are those employed on steam or electric with the control of train movements by one or more

tems are those employed in large central station sion and distribution systems, in connection the distribution system by one or more load

s are used in connection with the patrol of trans- trolmen to communicate quickly with headquarters; he U. S. Life-Saving Service.

ems for general communication have numerous and tions on steam and electric railways, and in connection with , transmission and distribution systems, etc.

communicating systems are designed for isolated local ually without attendance, in factories, mills, shops, residences, etc.

STANDARD TELEPHONE INSTRUMENTS

13. Speech is transmitted electrically by means of three supplementary elements, termed the transmitter, the line, and the receiver. The sound waves of the voice impinge upon the diaphragm of the transmitter and cause it to vibrate in substantial synchronism with the impressed disturbance. The diaphragm forms part of an electromechanism which establishes in the line circuit an alternating current of variable frequency, amplitude and wave form, but substantially proportional at any instant to the pitch, intensity and quality, respectively, of the impressed sound. The line current in its passage over the line suffers both loss of intensity, or attenuation, and change of wave shape, or distortion. If not too greatly enfeebled or distorted by its passage over the line, the transmitted energy enters the receiver and is there converted again into sound waves, approaching in pitch and quality the impressed sound waves at the transmitter. The receiver is an electromechanism whose function is the reverse of that performed by the transmitter.

The alternating line current, in certain instances, is superimposed on a continuous current, the resultant being a pulsating current. The two currents are separable either by means of a transformer, known in telephony as a repeating coil, or by a combination of reactance (choke) coils and condensers, sometimes termed a selective network.

14. Transmitters of the variable-resistance, granular-carbon type are almost universally employed. This type consists essentially of two parallel circular electrodes, usually of carbon, one of which is attached to the diaphragm, the other being rigidly mounted. Between the electrodes is a loose mass of finely granulated carbon. Vibration of the diaphragm causes simultaneous variations of pressure on the granular carbon, with accompanying changes in total resistance from electrode to electrode; the resistance decreases with increase of pressure, and *vice versa*.

15. High-resistance transmitters, having about 30 to 60 ohms average resistance, are ordinarily employed for both common-battery and local-battery (magneto) sets. High resistance is particularly desirable in common-battery sets, with central energy supply; it also has the advantage, in local-battery sets, of being economical in energy consumption.

16. Low-resistance transmitters, having about 10 to 15 ohms average resistance, are used in special service (local battery) where the transmission requirements are severe, such as railway train dispatching. Special low-resistance transmitters intended to operate from 110-volt direct-current lighting circuits are used in connection with loud-speaking telephones for announcing trains, paging guests in hotels, etc.

17. Solid-back transmitter. Fig. 1 shows a cross-section of what is commonly known as the White or solid-back transmitter. In this, P is the bridge mounted securely at its ends on the front, F. The diaphragm, D, is of aluminium, with its edges enclosed in a soft rubber ring, *e*, and is held in place by two damping springs, *ff*. W is a heavy block of brass, hollowed out to receive the rear electrode, B, which is of carbon secured to the face of a metallic disc, *a*. E is the front electrode, also of carbon, carried on the head of a metal stud, *b*. This electrode is clamped to the diaphragm by means of a

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threaded stud, *p*, and the thumb nuts, *tt'*. Against the front electrode is clamped a mica washer, *m*, which serves to close the front opening of the electrode chamber, and thus prevents the granular carbon from falling out. The flexibility of the mica washer allows the front electrode to vibrate with respect to the carbon chamber. The interior wall of the chamber is lined with a paper ring, *i*, for insulation.

Another well-known type of solid-back transmitter is shown in Fig. 2. The hard-drawn aluminum diaphragm contains a recessed chamber or cup

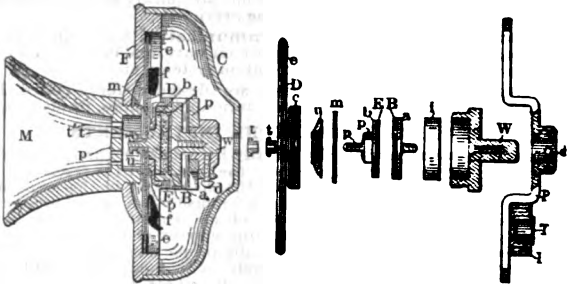


FIG. 1.—Cross-section and exploded view of solid-back transmitter.

which holds the front electrode, the granular carbon and the mica auxiliary diaphragm. The rear electrode is rigidly mounted on the bridge or solid back support. A hard aluminum sealing ring is riveted over the mica auxiliary diaphragm to render the carbon chamber both dust and moisture proof. The carbon electrodes are each copper plated on one face. A gasket serves to cushion the diaphragm against the casing and also insulates it electrically.

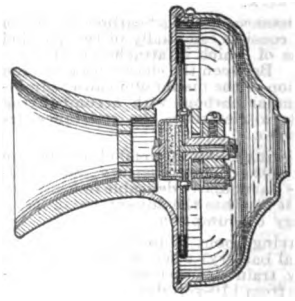


FIG. 2.—Cross-section of solid-back transmitter with recessed diaphragm.

Transmitters are sometimes made with one of the electrodes electrically common or in contact with the metal case of the instrument, but it is preferable to have both electrodes completely insulated, in order that users of the instrument may not come into contact with any part of the electrical circuits.

18. Transmitter batteries in local-battery sets are very generally composed of two dry cells (Sec. 20), connected in series. Wet cells were formerly used, but are more expensive, less compact and clean, and more difficult to handle. Two dry cells can be easily placed in the battery box of a wall set, making the set self-contained. Three dry cells will give slightly better transmission, usually, than two cells. Where the use is very severe, Fuller (wet) cells are used (Sec. 20), not less than two nor more than three cells being connected in series, for low-resistance transmitters. The latter type of cell is very well adapted for heavy local-battery service. At magneto switchboards either Fuller or Edison primary cells are suitable for supplying the operators' transmitters, when storage cells are not available or economical.

The energy supply in common-battery systems is obtained from the central battery at the switchboard, the current flowing from the switchboard over the line circuit to the telephone station and through the transmitter. A

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torage battery (Sec. 20) of 11 cells is usually employed. When the loudest ossible transmission is desired, low-resistance transmitters should be used, upplied from Fuller or Edison cells; storage cells, if they can be conveniently harged, will also be satisfactory.

19. Induction coils, when used, form a portion of the transmitting cir-uit and perform the function of a step-up transformer, in order to transmit o the line impulses or waves of higher potential than those produced in the ransmitter circuit. Induction coils are always used with local-battery ets, but not with all makes of common-battery sets (see Fig. 10). It is ery important to use the particular type and construction of induction oil which is designed for the transmitter with which it is associated; a ifferent type may operate with air satisfaction, but not with naximum efficiency.

The general construction of in-luction coils is shown in Fig. 3. The core consists of a bundle of mall iron wires; some manufac-urers employ annealed Norway ron. One manufacturer recom-nends a ratio of primary to sec-ondary turns, for local-battery ets, of one to four. The secondary is usually wound over the primary. Primary resistances vary from a fraction of an ohm up to about 10 ohms; econdary resistances range from about 20 to 150 ohms. Primary windings ange in size from No. 18 to 26 A.W.G. and secondary windings from No. 6 to 36. The diameter of the iron core is usually 0.25 in. minimum.

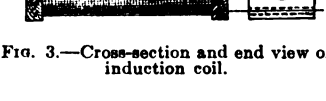


FIG. 3.—Cross-section and end view of induction coil.

20. Receivers consist essentially of three elementary parts, a permanent orse-shoe magnet, a sheet-iron diaphragm assembled in front of the magnet oles, and a winding on the polar extremity of each leg of the magnet. The normal tension on the diaphragm varies in synchronism with the current traversing the winding; thus when the winding is energized by voice currents, the diaphragm sets up corresponding voice sounds. Such an instrument is also reversible and may be used as a transmitter of the electromagnetic type; it is not efficient, however, and is used for this purpose only in emergencies, for example when the transmitter battery supply fails, to communicate with the switchboard operator. A modern telephone receiver is shown in Fig. 4. The working parts of this receiver are composed of two bar magnets clamped together by screws passing through an iron tail block, *b*, at one end and through a brass block, *c*, at the end nearest the magnet coils. The magnet unit, in one type, is welded to avoid the presence of joints. The pole pieces are clamped between the magnet ends and the brass block and on their outer ends by the two coils. The block engages a shoulder in the hard rubber shell nd is secured in place by screws, thus holding the working parts securely thin the shell. The diaphragm is clamped between the ear piece and the ain body of the shell. The terminals of the coils are led to the binding osts, *aa*, to facilitate connecting the receiver in the external circuit. The rd covering is secured to the tail block, *b*, so as to relieve the cord termi-ls from strain. A type similar in design but differing in that the dia-ragm, coils and magnets are all mounted on a separate metallic frame, ndependently of the enclosing shell, has the advantage that breakage of the ell does not necessarily destroy the adjustment of the instrument. Bipolar receivers are also made in the so-called "watch-case" type. This pe is attached to a head band and almost universally employed with opera-rs' sets for switchboard service.

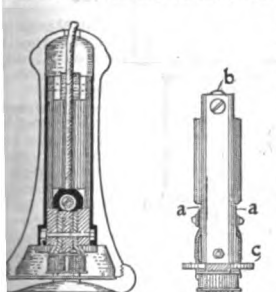


FIG. 4.—Cross-section of receiver and side view of magnets.

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21. Receiver terminals. Receivers are manufactured with both exposed and concealed terminals. The type with concealed and insulated terminals should always be used, in order that the user cannot come into contact with any portion of the electrical circuits.

22. Continuous-current receiver. A type of receiver in which the permanent magnet is replaced by an iron core, solid or laminated, is used in some instances with common-battery sets. The receiver winding is connected in the line directly in series with the transmitter, and the magnets are energised by the line current. This eliminates the necessity for an induction coil and results in a less expensive set for local or intercommunicating service. (See Fig. 10.)

23. Receiver resistance and impedance. Receivers are wound for various resistances from 30 to 100 ohms. A resistance of 70 to 80 ohms is very widely used for standard bipolar receivers; the impedance to voice currents (equivalent single frequency, about 800 cycles per sec.) is about 300 ohms. For train-dispatching circuits, where numerous stations may be bridged across the line simultaneously, it is desirable to use receivers of higher impedance in order to avoid excessive transmission losses by reason of low-impedance bridges. For this service, one manufacturer winds receivers for a resistance of 600 ohms, having an impedance to voice currents of about 2,500 ohms.

24. Polarized bells or ringers are used to make audible announcement of incoming calls or signals at telephone stations. A typical form of ringer is

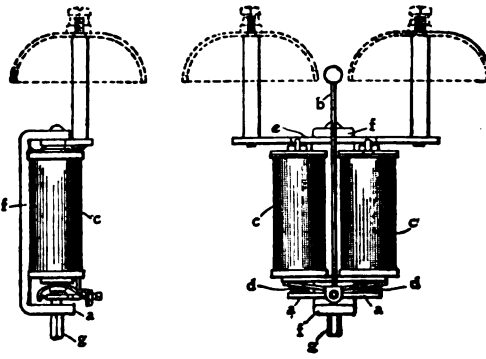


FIG. 5.—Polarised bell or ringer.

shown in Fig. 5. An iron armature *aa* is pivoted at its centre and carries a light rod *b* with a clapper at its outer end arranged to strike the gongs when set in vibration. Electromagnets *cc* are arranged with their pole pieces *dd* in position to attract the ends of the armature *a*; the magnetic circuit is completed by the yoke *e*. A permanent magnet *f* serves to polarise the armature *a*. The air-gap is made adjustable by means of the screw *g*. The magnet windings are connected in series.

A condenser (Par. 30) is frequently connected in series with a polarised bell when alternating current is used for signalling, and almost invariably has no harmful effect on the efficiency of the ringer itself; furthermore, a small condenser connected in series with the ringer increases the bridged impedance and thus improves the efficiency of signalling on heavily loaded party lines.

25. The resistances of polarised bells range from 80 ohms, for series ringers, to 3,500 ohms for bridging sets on heavily loaded party lines. Series ringers (80-ohm) are not now used to any great extent. The standard resistances for bridging ringers are 500, 1,000, 1,600, 2,000, 2,500 and 3,500 ohms.

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1,000-ohm ringers are standard for ordinary lines, while the higher resistances are used for party lines.

26. Magneto generators are commonly used for signalling from local-battery (magneto) stations or sets. A typical 3-bar magneto, or hand-generator, is shown in Fig. 6, unmounted. An armature of the Siemens or shuttle type is arranged to revolve in the magnetic field produced by permanent

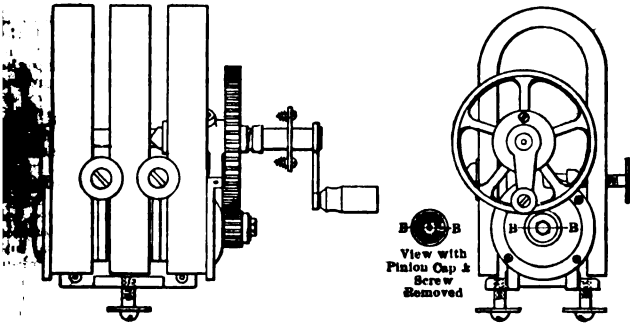


FIG. 6.—Magneto generator.

magnets, being driven through light spur gears increasing the speed in ratio of about 5 to 1. Therefore when the crank is revolved at 200 rev. per min., the frequency will be about 17 cycles per sec.; probably the average frequency is between 10 and 15 cycles.

The **series type**, for series sets (Par. 25), must be provided with an automatic short-circuiting device to remove it from circuit when not in use. The shunt or **bridging type**, for bridging sets (Par. 24), must be provided with an automatic circuit-opening device to disconnect it from circuit when not in use. These automatic switches are operated by the shaft which carries the generator handle and large spur gear. Fig. 7 shows the circuit of a bridging generator; the shaft *b* is so arranged that it will advance against a coiled spring and engage the spring *c* before rotating the spur gear, thus closing the circuit between the terminals *aa*. In one make of generator, a device is also provided to separately short-circuit the generator armature when out of use, in order to protect it from lightning or excessive foreign potentials.

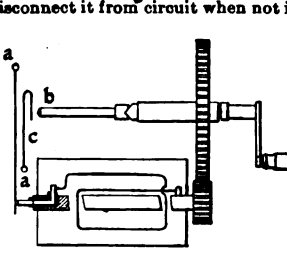


FIG. 7.—Diagram of magneto generator connections.

27. Magneto generator windings and ratings. The output of these generators, owing to their small size and high internal impedance, is very limited. The lower the internal impedance and the larger the magnetic flux through the armature, the greater will be the output for a given size and speed. The windings vary in resistance, in different sizes and makes, from about 100 to 500 ohms, with several thousand turns. The best grade of magnet steel (Sec. 4), with maximum retentivity and minimum aging, should be used. Generators for light service are usually equipped with three magnets, and are known as the 3-bar type; four bars are used for medium service and five for heavy service. The generated effective e.m.f. at no load and 1,000 r.p.m. (armature speed, giving 16.7 cycles per sec.)

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is about 70 to 80 volts. The voltage falls very rapidly as the output increases; the maximum output is of the order of only a few watts, probably rarely exceeding 5 watts.

28. Receiver hook. The receiver of a telephone set, when not in use, is hung on a hook which is termed the receiver hook or switch hook, and performs a very important function. The exposed metal portions of the hook should be well insulated from the circuits of the switch.

29. The hook switch, which is actuated by the hook, serves to close the talking circuits when the receiver is removed from the hook for use, and in addition performs several auxiliary functions. The other functions of the hook switch will be made clearer by reference to Figs. 8 to 13. In common-battery sets, the hook switch in addition serves as a means for signalling the switchboard through the agency of line relays or signals which cause a proper indication to be displayed before the operator.

30. Condensers are described as a whole in Sec. 5. The type of condenser usually employed for telephone purposes is commonly known as the "rolled condenser," made of tin-foil and paper and impregnated with paraffin, the whole being sealed in a moisture-proof case.

Telephone condensers are usually subjected to a test of 500 volts, continuous e.m.f. and required to have an insulation resistance of many megohms. Special condensers are constructed to withstand pressures of 1,000 volts, alternating. Standard condensers are made in a considerable number of sizes, ranging from 0.05 to 2 mf. Larger sizes can be made, but it is common practice to connect a number of condensers in parallel when more than 2 mf. is needed. The capacity of paraffin condensers is not sufficiently constant to permit them to be used as standards (Sec. 5). The impedance of a 1-mf. condenser at 16.7 cycles per sec. (2,000 alternations per min.), which is the standard ringing frequency, is 9,540 ohms; at 800 cycles per sec., the impedance (neglecting the leakage current and internal losses) is 199 ohms, and in both cases this impedance is wholly capacity reactance (Sec. 2). Condensers are used very extensively in telephone apparatus.

31. There are two general types of local line for connecting telephone stations with each other, or with a switchboard. The type by far most extensively used is the **bridging line,** to which the stations or sets are connected in the familiar shunt or bridging relation, like incandescent lamps in a constant-potential distribution system. The other type, but little used, is the **series line,** to which the stations are connected in series or looping relation, like arc lamps in a constant-current series distribution system.

32. Metallic lines are those composed throughout of insulated wires or conductors, and may be of the bridging or the series type. A bridging metallic line requires two wires, often termed a pair, at every point. The latter type is the preferable one for nearly every kind of private telephone system, except possibly for small interior intercommunicating systems.

33. Grounded lines are those composed in part of insulated wires or conductors, with earth or ground return, and may be of the bridging or the series type. Grounded lines are not recommended, because of the insuperable difficulties from cross-talk and other disturbances, so frequently present.

34. Magneto or local-battery bridging sets (Fig. 8) have been described in Par. **26.**

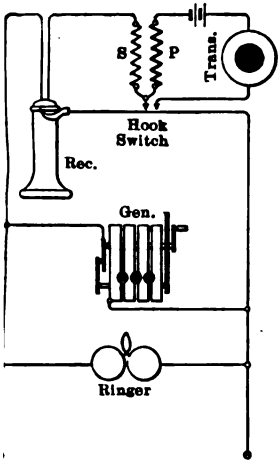
35. Magneto or local-battery series sets are typified by the set depicted in Fig. 9 and described in Par. **27.** They are not extensively used.

36. Bridging sets (Fig. 8) are those adapted for use on bridging lines (Par. **31**). The receiver and the secondary of the induction coil are in series relation with each other, and bridged across the line through the contacts of the hook switch, the latter being closed only when the receiver is off the hook, as shown in Fig. 8. The ringer is separately bridged across the line, and likewise the generator, although the circuit of the latter is closed only when it is in action. The local battery circuit of the transmitter is closed by the hook switch, only when the receiver is off the hook. The set shown in Fig. 8 is the magneto or local-battery type; common-battery bridging sets are shown in Figs. 10 to 13.

37. Series sets (Fig. 9) are those adapted for use on series lines (Par. **31**). The receiver and the secondary of the induction coil are in series relation with

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ach other, and connected to the instrument terminals through the contacts f the hook switch, the latter being closed only when the receiver is off the ook, as shown in Fig. 9. The ringer and the generator are connected in eries with each other, and stand normally connected to the instrument



IG. 8.—Circuit diagram of typical bridging telephone set.

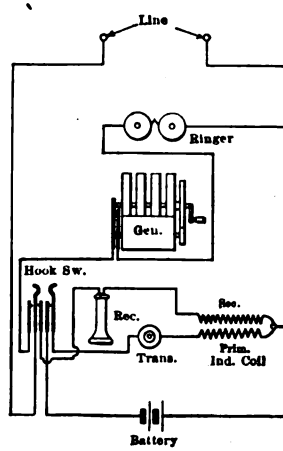


FIG. 9.—Circuit diagram of typical series telephone set (Stromberg-Carlson).

rminals when the receiver is on the hook, but are disconnected when the ceiver is in use. The generator is short-circuited except when in action.

38. Common-battery bridging sets are illustrated in Figs. 10 to 13. he simplest type of circuit appears in Fig. 10. The transmitter current is btained over the line circuit from the central battery at the switchboard.

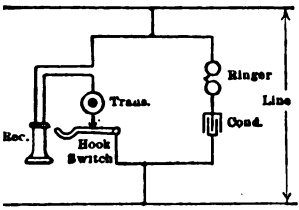


FIG. 10.—Circuit diagram of typical mmon-battery bridging set without duction coil.

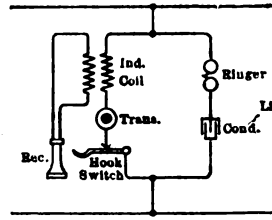


FIG. 11.—Circuit diagram of typical common-battery bridging set with induction coil.

eceivers of the permanent-magnet or polarized type must be properly lled, so that the transmitter current will strengthen their magnets instead weakening them. Continuous-current receivers (Par. 22) are sometimes used in this type of set.

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A similar type of set, modified to the extent of employing an induction coil and placing the receiver in a local circuit, is shown in Fig. 11. The Kellogg Switchboard and Supply Company's set is shown in Fig. 12. In the latter type the transmitter circuit is completed through a 25-ohm retardation coil which is shunted by a circuit composed of the receiver and a condenser in series. The Western Electric Company's set is shown in Fig. 13. These types are representative of modern practice; other methods of wiring can be obtained from manufacturers' bulletins.

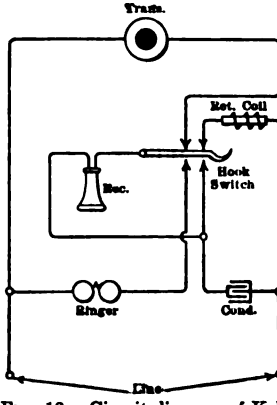


FIG. 12.—Circuit diagram of Kellogg common-battery set.

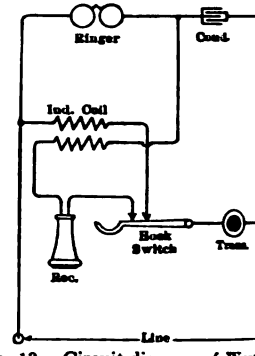


FIG. 13.—Circuit diagram of Western Electric common-battery bridging se

LOCAL-BATTERY MANUAL SWITCHBOARDS

39. The essential elements of a manual switchboard are the li terminals or jacks, the line signals and the switching mechanisms; th last are comprised of pairs of cords and plugs, with their associate talking and ringing keys, supervisory signals, and the operators' talkin sets. In very small manual boards the pairs of cords and plugs are some times replaced by keys, so arranged and wired as to perform the desired switching operations at will.

40. Non-multiple switchboards are those in which there is but one terminal or jack for each local line. Therefore this type of board is limited in size by the fact that each operator at the board must be able to reach every line terminal, unless local or transfer trunks are provided from one operator's position to another. It is not the practice to handle any considerable amount of traffic by means of transfer trunks, but instead to resort to multiple boards (Par. 41). The limit of size of a non-multiple board is usually about 400 lines, with two operator's positions; 600-line boards with three positions and transfer trunks from the first to the third position are employed, however.

41. Multiple switchboards are those in which there are two or more terminals or jacks connected in multiple to each line, in such a manner as to provide for each line at least one jack within the reach of each operator. For this means transfer trunks are made unnecessary and any operator can connect together any pair of lines in the switchboard. Multiple boards are made in many sizes, from a few hundred lines up to 10,000 lines. Local-battery multiple boards are not now employed for installations of more than a few hundred lines, because of the greater economy of common-battery multiple boards.

42. Switchboard line signals in local-battery or magneto systems are usually **drops**, which commonly consist of an iron-clad electromagnet with

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an armature arranged to disengage a shutter and display the number of the calling line, when the drop winding is energized by an incoming ringing current. The drop shutter is also arranged to close a pair of local contacts for sounding an auxiliary calling signal termed the "night alarm." Drops

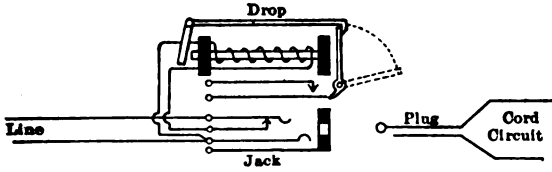


FIG. 14.—Circuit diagram of line jack and drop in non-multiple magneto switchboard.

are made in some cases with a restoring coil which serves to return the shutter to normal position when the operator answers the call by inserting a plug in the answering jack (Par. 43); in other cases the drop and the answering jack

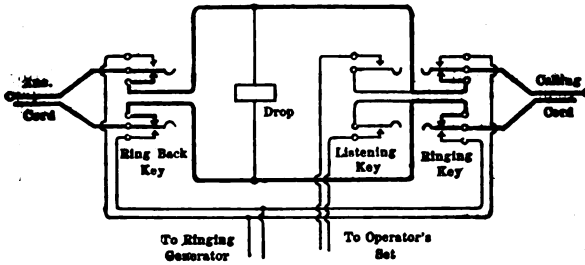


FIG. 15.—Circuit diagram of cord-circuit in non-multiple magneto switchboard; single clearing-out drop.

are mounted together and so arranged that the plug restores the shutter mechanically when the plug enters the jack. The terminus of the line circuit is usually wired as indicated in Fig. 14. Drops are wound of various resistances from 80 ohms to 1,000 or 1,200 ohms; a resistance of 500 to 600 ohms is very commonly used.

43. Switchboard line jacks for non-multiple magneto boards are usually of the type illustrated in Fig. 14. The drop is disconnected from one side of the line by the insertion of the plug in the jack. The night-alarm contacts are shown just below the drop winding.

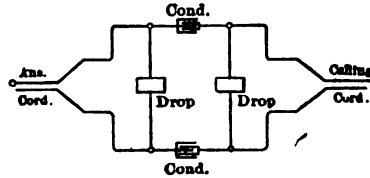


FIG. 16.—Circuit diagram of cord-circuit with double clearing-out drops, for double supervision.

44. The wiring of a cord circuit with ringing keys, listening key and single supervisory drop is given in Fig. 15. The wires of the through talking circuit are shown in heavy lines. There is some disadvantage in having but one supervisory drop, since it is not possible for the operator to predetermine which line is signalling for attention. This difficulty is overcome in the cord circuit which appears in Fig. 16 (keys not shown), inasmuch as

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the condensers tend to shunt the low-frequency ringing current through the nearest drop instead of permitting it to pass readily along the cord circuit to the other drop or any other bridged apparatus.

45. Repeating-coil cord-circuits are employed where it is necessary to connect metallic lines with grounded lines, or to reduce the inductive disturbances which sometimes occur when two metallic lines are connected together by a straight cord-circuit (Fig. 15). A cord circuit with a repeating coil is shown in Fig. 17, with ringing and listening keys omitted from the diagram. Sometimes the repeating coil is connected to the cord circuit through the contacts of a special key, so that the coil may be cut into circuit at will. The transmission will be more efficient with a straight cord than with one having a repeating coil in circuit, and therefore such coils should be used only when necessary to reduce inductive disturbances or line noise.

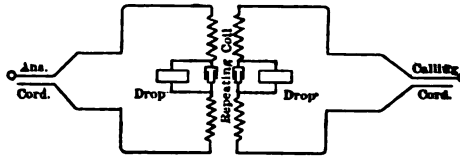


FIG. 17.—Circuit diagram of cord-circuit with repeating coil and double supervisory drops.

46. Commercial sizes of non-multiple magneto switchboard are usually limited to not more than 600 lines, arranged and equipped for not more than three operators' positions. The following sizes are standard with the Kellogg Switchboard and Supply Co.

Lines	Operators' positions	Pairs of cords per position	Lines	Operators' positions	Pairs of cords per position
20	(Wall type)	5	250	2	12
50	1	10	300	2	15
100	1	10	350	2	15
150	1	15	400	2	15
200	1	15	450	3	15
200	2	10 to 15	600	3	15

47. Transfer trunks for the purpose of transferring or trunking connections from one position to another, are not only convenient, but often necessary in these small boards, especially those arranged for three operators' positions.

48. Multiple jacks (Par. 41) are sometimes employed in boards of 400-line size and are very common in boards of 600 lines. The purpose of multiple jacks is to avoid the necessity of transfer trunks and the attendant extra labor in operation. The details of multiple magneto boards are beyond the scope of this section and the reader should consult the authorities mentioned in the Bibliography, Par. **263**.

49. Distributing frames or cross-connecting racks are installed in connection with switchboards of every type, and are intermediate in position between the incoming lines and the switchboard. This frame takes various forms, but is usually built up of light structural iron shapes, on one side of which are arranged the terminals of the incoming lines and their associated protectors, and on the other side are arranged the terminals of all the lines leading to the switchboard. By means of jumpers any outside or incoming line can be wired to any switchboard line, thus providing the necessary flexibility for distributing or grouping the lines in the switchboard in any manner desired.

There are two styles of distributing frames, known as the **main frame** and the **intermediate frame.** The former is the one described just above; the latter is used only in connection with multiple boards, being intermediate

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in position between the main frame and the board, for the purpose of enabling any answering jack to be associated with any set of multiple jacks.

50. Switchboard wiring is usually in cable, and the style of cable is commonly referred to as **switchboard cable.** This type of cable is made from various sizes of tinned annealed copper wire (Sec. 4), ranging from No. 18 to 24 A.W.G. The insulation, where the cable is for use in dry places, usually consists of two wrappings of silk and one of cotton; the conductors are twisted into pairs or triples, then a wrapping of paper is applied over all, next a wrapping of thin metal tape (lead, antimony and tin), and finally an outside cotton braid saturated with beeswax. The insulation of the individual wires is sometimes varied, using different combinations of enamel, cotton and silk. These cables are laid up in round, oval or flat cross-sections as desired, in twisted pairs or triples, ranging from 6 pairs to 100 pairs; 5, 10, 15, 20, 25, 30, 40, 50 and 100 pairs are approximately standard sizes. A code color scheme is employed in the cotton covering of individual wires, for the purpose of identifying the pairs and facilitating splices and connections; the manufacturers' bulletins give the codes employed.

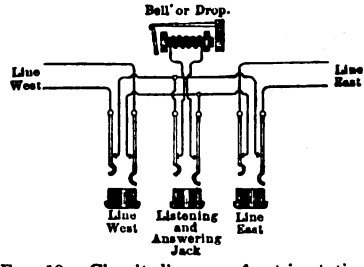


FIG. 18.—Circuit diagram of cut-in station or looping bridge.

Wool-insulated cable is now generally employed in place of pot-head wire (rubber insulated) for connecting underground or aerial cable terminals with the main frame, and in places where there might be trouble with ordinary cotton insulation on account of moisture.

Lead-covered interior cable, insulated with double silk and single cotton saturated with beeswax, is very useful for interior wiring in moist or damp places. It is standard in sizes of 5 to 40 pairs, by steps of 5, and 50, 60, 75, 100, 120, 150 and 200 pairs, of No. 22 A.W.G. tinned annealed copper.

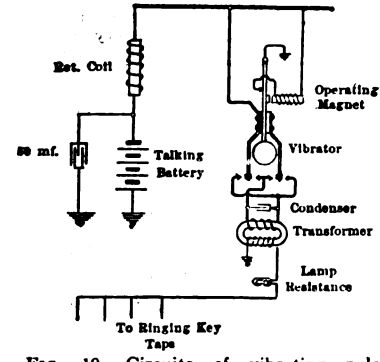


FIG. 19.—Circuits of vibrating pole changer for supplying ringing current from a battery source.

Twisted pairs should be used invariably for all **talking circuits** in order to avoid cross-talk. The length of one complete twist should not exceed 4 or 5 in.

51. Wiring of a through line is shown in Fig. 18. The middle jack is so wired that the operator can listen to determine whether the line is busy before attempting to use it. Code ringing must be employed on a through line connected in this manner. This style of jack wiring is termed a **cut-in station** or **looping bridge.** It can also be arranged with keys instead of jacks, and mounted in a special cabinet if desired.

52. Ringing energy can be obtained in three ways: (a) from a ringing dynamotor (Sec. 9) supplied on the primary side from a lighting or motor circuit, or from a storage battery (in common-battery installations); (b) from a hand generator (Par. 26) mounted in the switchboard; (c) from a

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vibrating pole-changer arranged to periodically reverse the impressed e.m.f. of a battery, usually composed of dry cells. In small installations a pole-changer and dry battery are very economical. The arrangement of a typical pole changer is indicated in Fig. 19, with its associated apparatus. When a dry battery is employed for ringing, it is customary to employ about 75 cells; the use of a transformer as shown in Fig. 19 then becomes unnecessary. Another type of vibrator employs but one vibrating contact, and requires two groups of dry cells, about 75 cells per group, connected in series and grounded at the centre; the vibrator makes alternate connections with each group.

COMMON-BATTERY MANUAL SWITCHBOARDS

53. The central battery supplies the energy for both talking and signalling, at the stations as well as the switchboard. The method of signalling from the switchboard to the stations is the same as that described under "Local Battery Manual Switchboards," Par. 39 to 58. The method of signalling from the stations to the switchboard, however, consists of moving the receiver hook up and down to interrupt the line circuit and thus interrupt the flow of current from the central battery through the line signal, over the line to the station, and return. The battery is customarily grounded on the positive side, and the "tip" side of the line is the grounded side, while the "ring" or "sleeve" side is the battery side.

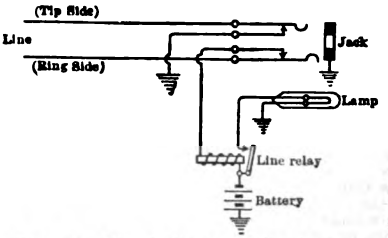


FIG. 20.—Circuit diagram of line jack, relay, and lamp in non-multiple common-battery switchboard.

54. The line circuit forming the terminus of a local or station line in a non-multiple common-battery board is shown in Fig. 20. The line signal consists of a lamp associated with the line jack; this lamp becomes energized when the receiver is removed from the hook at the distant station, and is de-energized again when a plug is inserted in the line jack in response to a call.

55. Commercial sizes of non-multiple common-battery boards are given in the following table, representing two of the leading makes.

Lines		Operators' positions	Pairs of cords per position		Transfer trunks
Common battery	Local battery		Common battery	Combination	
75	20	1	7	3	8
100	.....	1	10	.....	8
120	20	1	10	5	14
160	.....	1	15	.....	14
200	20	1	10	5	14
240	.....	1	15	.....	14
200	50	1	10	5	10
280	20	2	11	4	28
320	.....	2	15	.....	28
400	.....	2	15	.....	40
440	20	2	11	4	28
480	.....	2	15	.....	28
600	.....	3	15	.....	60

The Western Electric Company manufactures a sectional unit type of central-battery private exchange switchboard, for not more than 100 lines, which comprises a supporting unit, a cord unit, one or more line units and a top unit. This equipment is very flexible and adaptable to a variety of different local requirements.

56. Cord circuits are arranged in several ways, according to the method used for supplying transmitter current to the local lines. Fig. 21 illustrates

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one type of cord circuit, complete with ringing and listening keys; this type employs a repeating coil, and is used by the Western Electric Co. in some types of non-multiple boards. The lamps are termed supervisory signals,

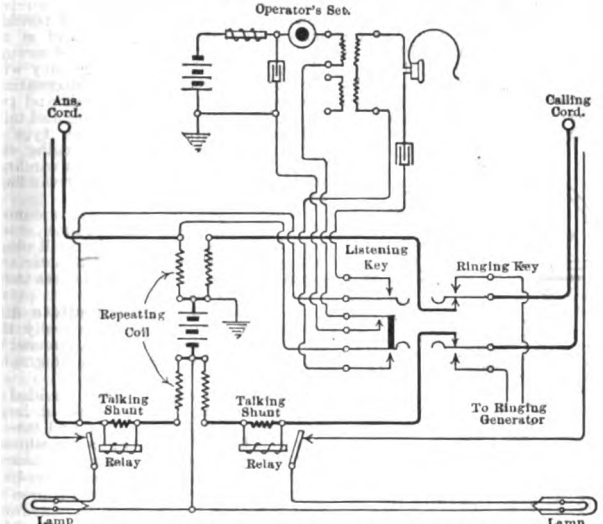


FIG. 21.—Cord circuit for non-multiple common-battery switchboard.

and will be lighted whenever the receiver hook at the line station is depressed. In some types of cord circuit a retardation coil is employed instead of a repeating coil. Combination cord circuits are those specially wired for the purpose of connecting common-battery lines with local-battery lines.

87. Retardation and repeating coils are quite similar in general construction, but differ in their windings. The principal types of simple impedance or retardation coils are shown in Figs. 22 to 24. Soft Norway iron wire is commonly used in core construction; the **toroidal coil** in Fig. 24 is

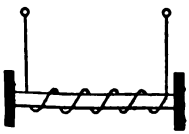


FIG. 22.—Impedance coil with open magnetic circuit.

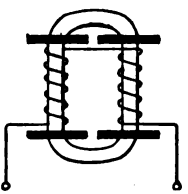


FIG. 23.—Impedance coil with closed magnetic circuit.

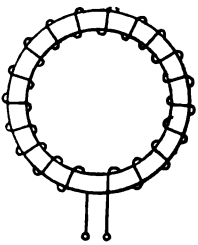


FIG. 24.—Toroidal type of impedance coil.

usually constructed with very fine iron wire covered with a very thin insulation of cellulose or enamel to reduce the eddy-current losses. The desired properties of the iron are high permeability, high resistivity and low hysteresis loss. Enamel insulation for the electrical windings is the most economical

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of space, although cotton and silk are sometimes employed. The windings should be vacuum baked and impregnated.

Commercial repeating coils are made in various types, corresponding to the retardation coils above described. The toroidal type, properly constructed, is one of the most efficient coils known. A completely balanced toroidal coil is shown in Fig. 25. The terminals *l* are the line terminals and *m* are the middle taps. A toroidal type of coil for common-battery cord circuits has four windings of 21 ohms each, being designed for high efficiency with talking currents, but not especially efficient for ringing (16-cycle, alternating currents. A larger coil, with two outer windings of 35 ohms each and two inner windings of 30 ohms each, has high efficiency for both ringing and talking, thus suiting it for phantom and simplex circuits. Another type of simplex coil having high ringing efficiency, is wound with two inner windings of 45 ohms each and two outer windings of 36 ohms each.

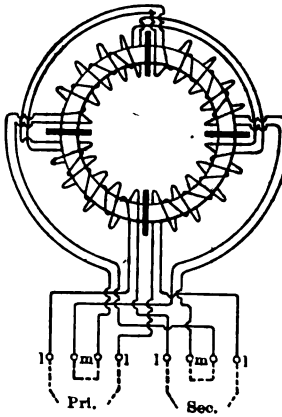


FIG. 25.—Toroidal type of repeating coil; four balanced windings.

When repeating coils are mounted close to each other, base to base, cross-talk from one coil to another will result unless they have closed magnetic circuits and are enclosed in iron cases to reduce stray fields.

58. Main and intermediate distributing frames are practically the same as for magneto boards, covered in Par. 49. Also see the bibliography Par. 263.

59. Relay racks are also provided in common-battery installations of large size, for mounting the line and cut-off relays. The cord-circuit apparatus should be mounted if possible in the switchboard.

60. Power plants for common-battery switchboards comprise a source of energy for the talking circuits, relays and lamps, and a source of energy for signaling or ringing purposes. The former source usually consists of a storage battery (Sec. 20) of 11 cells, giving normally 22 volts; in some cases 22 cells are used to meet especially severe transmission requirements. In very small installations primary batteries (Sec 20) are sometimes used, if no source of primary energy is accessible.

61. Battery-charging generators are different from standard direct-current machines (Sec. 8) in two respects. They have smooth-core armatures and more than the usual number of commutator segments, in order to supply as nearly as possible an absolutely continuous current. Otherwise the minute but very rapid pulsations in the current, caused by armature core teeth and commutation, will give rise to slight pulsations of potential at the battery terminals and make the telephone lines noisy during charging.

62. Ringing generators for supplying both alternating and pulsating current at various fixed frequencies from 16 to 66 cycles per sec. are in general covered in Sec. 9, under Dynamotors, or in Sec. 7 and 8 under Generators. Machines of the dynamotor type are wound for operation from 22-volt, 115-volt and 230-volt direct-current sources, and deliver from 75 to 100 volts alternating. Ringing dynamotors are standard in sizes rated from about 25 watts, suitable for small offices, up to about 1 h.p. for large exchanges. Each ringing tap is fused and a lamp resistance is connected in series in order to prevent excessive currents in the event of ringing on a short-circuited line.

63. Prevention of battery noise in common-battery installations, caused by the small but very rapid pulsations or ripples (Par. 61) in the current delivered by the charging machine, sometimes requires a circuit arrangement which is illustrated in theory in Fig. 26. The function of the condenser is to short-circuit the ripples of e.m.f. from the generator, which are of high frequency, while the impedance coils tend to suppress the cur-

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responding ripples of current in the battery circuit. In large installations, especially with large batteries (of very small internal impedance), the condenser is seldom required. This device can be wholly dispensed with when modern charging generators (Par. 61) are employed.

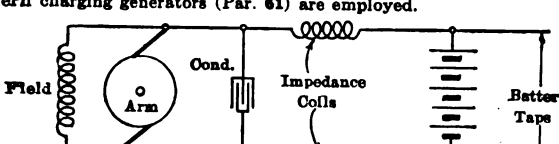


FIG. 26.—Method of suppressing battery noise caused by generator or motor operation.

AUTOMATIC SWITCHBOARDS

64. Fundamental features. There are two general types of automatic systems, the **full automatic** (Par. 65 to 72) and the **semi-automatic** (Par. 73 to 75). The former type performs all switching operations by means of automatic mechanisms under the control of the selector dials or calling devices at the telephone stations; the latter type requires switchboard operators, as in the manual system, but the dial and its functions are transferred from the subscriber to the operator.

65. Numerous systems have been invented and reduced to commercial practice, including the Strowger, the Lattig-Goodrum, the Lorimer, the Bullard-Rorty and the Clark systems. These systems are all complicated when viewed in their entirety, and cannot be described in the space here permitted. The following description, Par. 66 to 72, covers the system of the Automatic Electric Co. (Strowger) as developed for small installations not exceeding 100 lines.

66. Telephone sets for automatic service are equipped with **calling devices**, one of which is shown attached to a desk stand in Fig. 27. The circuit diagram of this set is given in Fig. 28. The calling device consists of a **dial** with ten holes, which are numbered with the ten digits, consecutively from 1 to 0. In order to call line No. 73, for example, the person calling first removes the receiver from the hook and then, placing his finger in the seventh hole, pulls the dial around until his finger engages the stop, which causes seven impulses (which are really interruptions of a steady current) to pass over the line to the switchboard; he then places his finger in the third hole and repeats the operation, whereupon the automatic switching mechanisms connect the calling line with line No. 73 and ring the station. When someone answers at station No. 73, the ringing current is automatically cut off and the talking circuits are clear.

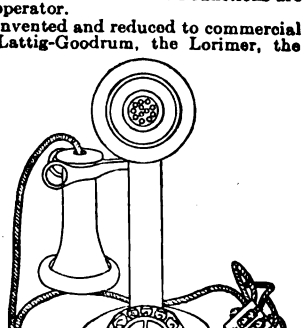


FIG. 27.—Derk stand equipped with dial.

The mechanism of the calling device is shown in Fig. 29. The dial winds a spring which drives an interrupter, consisting of a fibre cam engaging the impulse springs; a tiny ball governor is attached, which insures uniform speed. The line circuit is normally closed (when the receiver is off the hook) and an impulse, so-called, is really a brief interruption of the line current.

67. Line switch. Each line terminates at the central office in a line switch, whose function is automatically to connect the line to an idle connector as soon as the receiver is removed from the hook. For the sake of simplicity the line switch is omitted from the accompanying illustrations. The lines are also multipled to the connector banks (Par. 65). Each line might,

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if desired, terminate in a connector, but the provision of line switches is more economical because it makes possible a reduction in the number of connectors.

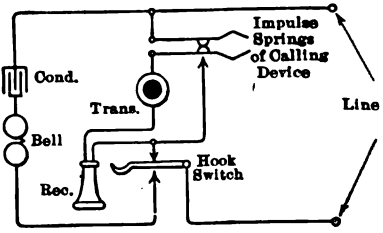


FIG. 28.—Circuit diagram of bridging common-battery set for automatic system.

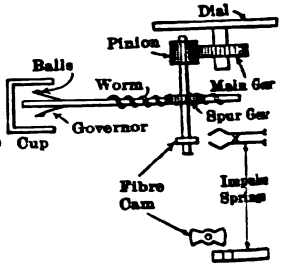
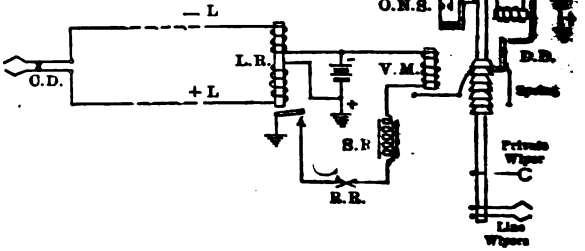


FIG. 29.—Skeleton diagram of mechanism of calling device.

68. Connectors. The circuits of a line connected to a connector (omitting the intermediate line switch) are shown in Fig. 30. The principal features of the connector mechanism are illustrated in Fig. 31. Each switch consists of two principal parts: first, the shaft, carrying brushes or wipers and equipped with two magnetically operated ratchets and pawls, one of which is



C.D.—Calling device.
L.R.—Line relay.
S.R.—Series relay.
R.R.—Release relay.
R.M.—Release magnet.
O.N.S.—Off-normal switch.
D.D.—Double dog (detent).
V.M.—Vertical magnet.

FIG. 30.—Theoretical diagram of a connector.

adapted to impart a vertical step-by-step movement to the shaft, and the other a rotary step-by-step movement; second, the contacts over which the brushes or wipers are made to pass by means of these two movements. The contacts are arranged in banks, 10 rows high and 10 rows wide, or 100 in all.

69. Operation. The line relay causes the first set of impulses to actuate the vertical magnet and step the wipers up to the corresponding row, which would be row No. 7 in the case of a call for line No. 73. Meanwhile the series relay is energised by these impulses, and preserves the vertical magnet circuit even though the off-normal springs (*ONS*) have operated at the first upward step of the wiper shaft, and switched the pulsations onto the main contact spring of the series relay. The latter, being slow-releasing, remains constantly energised during the series of rapid impulses. When the first set of impulses has ceased, the series relay is de-energised and switches the impulse circuit to the rotary magnet. (See Fig. 32.)

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The second set of impulses actuates the rotary magnet and rotates the shaft until the wipers rest on the corresponding set of contacts, which would be the third set in the seventh row, in the case of a call for line No. 73. During this second set of impulses, the rotary-magnet relay (*E*) has been constantly energised and has maintained the rotary magnet circuit even though the busy-test relay may have opened and closed its contact *G*. Relay *E* also holds the private wiper (*PW*) open during rotation.

When the second set of impulses ceases, the slow-release relay *E* falls back, and closes the private wiper circuit. If the called line is busy, there will be a ground on the private bank contact, so that the wiper-closing relay (*WCR*) cannot operate. But if the line is free, current will flow through the 125-ohm winding of the wiper-closing relay and the cut-off relay (*COR*) of the called line. The latter clears the called line of attachments, the former connects the line wipers to the source of intermittent ringing current. When the called station answers, the ring cut-off relay stops the ringing and connects the two subscribers together.

When the receiver at the calling station is returned to the hook, the slow-acting release relay (Fig. 32) is de-energized by the line relay and thus releases the double-dog (Fig. 30) and the wiper shaft returns to normal, clearing the connection. The off-normal switch serves to keep open the circuit of the release magnet unless the wiper shaft is in action or use.

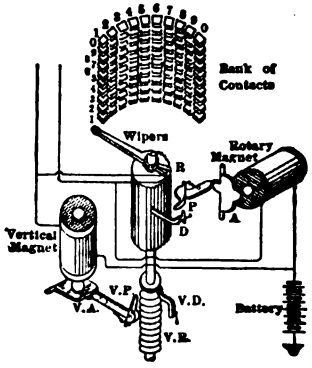


FIG. 31.—Connector switch.

For the sake of simplicity certain details have been omitted, but the essential principles have been emphasized as fully as space will permit. The busy test, which is not shown, is so arranged that a call for a busy line will not be completed, and the usual busy signal will be communicated to the calling line. For further details see the references below* and the Bibliography (Par. 263).

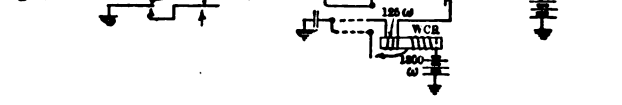


FIG. 32.—Details of connector circuit.

70. Mounting. Line switches are usually mounted in groups of 100 each. The necessary connectors for a group of 100 lines are mounted with

*Campbell, W. L. "A Study of Multi-office Automatic Switchboard Telephone Systems;" *Trans.* A. I. E. E., Vol. XXVII, 1908, p. 503–541.
Campbell, W. L. "A Modern Automatic Telephone Apparatus;" *Trans.* A. I. E. E., Vol. XXIX, 1910, p. 55–84.
Smith, A. B. and Campbell, W. L. "Automatic Telephony;" McGraw-Hill Book Co., Inc., New York, 1914.
Smith, A. B. "Applicability of Automatic Switching to All Classes of Telephone Service;" *Trans.* A. I. E. E., Vol. XXXVIII, 1919, p. 1567.

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the line switches, forming a 100-line unit. The number of selectors or connectors required for each 100 lines depends upon the volume of traffic during the busiest period.

71. Selectors. When there are more than 100 lines, it becomes necessary to employ selectors. The first selectors are connected to trunks leading to the connectors. The first group of impulses in a number, say line No. 528, controls the vertical movement of the shaft of the first selector; the rotary movement of the shaft, however, is automatic and continues until the wipers rest on the contacts of the first idle trunk to the connectors in the 500 group. The second and third sets of impulses respectively step up the shaft of the connector to the second row of contacts and rotate the shaft to the eighth set of contacts, completing the connection to line No. 528. In order to call a number containing four digits, second selectors are necessary; five digits, third selectors, etc.

72. Costs. The cost per line of the central office equipment (Strowger automatic) completely installed and including the station equipment, uninstalled, for a private automatic exchange of 200 lines, is approximately $55 to $60 per line.

73. Semi-automatic systems of several types have been produced, including the North Electric (Automanual) and the Western Electric systems. The general features of semi-automatic systems have been described in Par. **64.**

74. Clement or automanual system. In this system the station equipment is the same as in manual common-battery practice. When the receiver is removed from the hook at the calling station, the line is automatically connected to the first idle **primary selector** (of the 100-line type), which automatically steps in the rotary and vertical motions until its **test brush** connects with the calling line terminal. The test brush, in arresting the switch in connection with this line terminal, also energizes the cut-off relay of the calling line and establishes an electrical "busy" guard against incoming calls. Simultaneously an idle **key-set switch** (100-line type) is automatically placed in operation, and this switch automatically selects the occupied primary selector and conveys the call to the first idle operator. The last operation lights a key-set line lamp and the operator answers by pressing the answering button, which places her in communication with the calling station.

Upon receiving the desired number, the operator sets up that number on the key set (which is similar to the adding machine) and if a party-line designation is given, a button corresponding thereto is also pressed, and the call is then completed (so far as the operator is concerned) by pressing the starting button of the key set. The call is from this point taken up by the key-set switch, which controls the emanation of impulses from the sending machine, as indicated by the depressed buttons of the key set. The first series of impulses being in the thousands, are directed to the **first selector** which is associated with the primary in use. This first selector is propelled rotarily by the impulses, designated in the thousand-row buttons in the key set, or if the call is for another exchange, to the row of contacts on which the trunks between the exchanges are terminated and automatically tests up the row in the vertical position until its brushes are connected with an idle trunk. This trunk connects with an idle **second selector** which receives the impulses as indicated in the hundred row of buttons of the key set rotarily and automatically tests for an idle connector vertically.

The next series of impulses controlled by the key-set ringing buttons sets up the party-line **ringing selector** associated with the first idle **connector** (of the 20-point distributing switch type) and the tens and unit impulses, as indicated on the key set, are directed respectively to the rotary and vertical movement of the connector switch (of the 100-point type); this brings into connection the test relay, which, if the called line is busy, is actuated to connect busy-back tone to the calling subscriber and if not busy, connects the ringing current to the called line and actuates the cut-off relay of the called line, making this line busy to all other connectors. At this point, the key-set switch releases from the trunk and is made immediately available for connection with other calling primaries and the connection is then controlled entirely from the calling and called stations; by manipulating the receiver hook either station may disconnect for immediate recall.

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76. Trunking between automatic and manual switchboards can be readily provided by means of appropriate apparatus, and is extensively employed. For details of such trunking in exchange systems see the Bibliography (Par. 263).

INTERCOMMUNICATING SYSTEMS

76. Intercommunicating systems comprise relatively compact private telephone systems, in most cases without any switchboard or operating attendants, for the purpose of internal communication in factories, industrial plants, stores, offices, hospitals, residences, apartment buildings, etc.

77. Equipment. Each station is equipped with a telephone set and a switching device mounted in a small box or cabinet. For each station there is a telephone line or circuit extending to all other stations, and so arranged that by depressing the appropriate switching key or button in the switching cabinet at any other station, connection can be established with this particular line; at the home station there is also a calling signal or bell (or buzzer), and an answering key arranged to connect the home telephone set with the line. Thus for a 10-line system there will be 10 keys or buttons in each switching cabinet and 10 talking circuits in a small cable multipled to all 10 cabinets; in addition to the 10 line-circuits there is another pair for supplying the talking current (common battery) to each station, and still another pair for supplying ringing current to each station. Direct-current is usually employed for ringing, and dry batteries are used for both ringing and talking. The keys or buttons are usually so arranged that when depressed as far as possible, the ringing current is sent out on the line; when released, the key automatically returns to an intermediate position, where it is held by a lock or detent, and thereupon the ringing connection is broken and the talking circuit completed. The several keys in any individual switching cabinet are usually so arranged or interlocked, that the depression of one key automatically releases or restores all the others.

78. The operation is very simple. In order to call station No. 7 from station No. 3, the No. 7 button at station No. 3 is depressed as far as possible and held there a moment before releasing it, and meanwhile the bell connected to line No. 7, which is at station No. 7, responds. At station No. 7, the home button is depressed and the receiver taken from the hook, thus establishing communication. The ringing connection on the home button can be omitted, since it is obviously unnecessary.

79. Other equipment combinations can be arranged readily, including master stations for switching, with annunciator; one-way stations for inward calls only; non-selective code-ringing party lines, etc. The manufacturers offer many varieties of equipment for such combinations, which are readily understood from their bulletins.

80. The line capacity of standard equipments varies somewhat among the different manufacturers, but not to any great extent. One manufacturer offers complete units equipped for 6, 12, 22 or 32 stations; another offers sets for 11, 21 or 31 stations; another, 6, 12, 16, 20 or 24 stations, etc. These equipments are usually made in several styles, for desk mounting, wall mounting, or the flush wall type.

PHANTOM CIRCUITS

81. Two types of phantom circuits are in use, one derived by means of repeating coils, the other by bridged impedance coils. Both types are illustrated in theory in Fig. 33, all circuits being metallic.

82. The repeating-coil type of phantom circuit is shown in theory in Fig. 33, at the left of the diagram, where *RC* are repeating coils tapped at the centres of the line-side windings for the derived or phantom circuit.

83. The impedance-coil type of phantom circuit also appears in Fig. 33, at the right, where *IC* are retardation or impedance coils tapped at the centres of their windings for the derived or phantom circuit. This type is especially suitable for station circuits, where it is possible to economize in line wire by connecting the more distant stations to a phantom circuit. In this case grounded signalling cannot be employed. The side circuits should be substantially alike in all particulars, including length.

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This type may also be used for switchboard or office installations, instead of repeating coils, and in this case it is generally the practice to install a condenser in series with each side of the line, between the coil and the jack, as in a simplex set (Par. 116).

84. Identical side circuits should always be employed in deriving metallic phantom circuits, for the best results. This is necessary for the proper electrical balance of the phantom. Special transpositions are also required; see Par. 168 and 169.

85. Grounded phantoms, or half phantoms, can be obtained by connecting repeating or impedance coils to a metallic circuit and employing an earth return for one side of the phantom. This arrangement is open to the same objections which apply to the use of ground-return circuits in

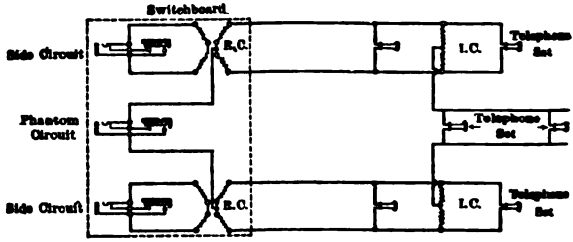


FIG. 33.—Phantom circuit.

general—namely, cross-talk and noise caused by lack of transposition and by earth potentials.

86. Phantom circuits in cable require specially constructed cables of the quadded type, described in Par. 150. This form of construction is essential in order to transpose the phantom and prevent cross-talk.

87. The repeating and impedance coils for phantom circuits should be carefully balanced electrically in order to prevent cross-talk between the side circuits and the phantom. The windings should be subdivided, grouped and balanced in such a way that the currents of the phantom circuit will induce (electromagnetically) no e.m.fs. in the side circuits and *vice versa;* see also Par. 57. The torroidal type of coil with two inner and two outer windings, 35 ohms per winding, is extensively used.

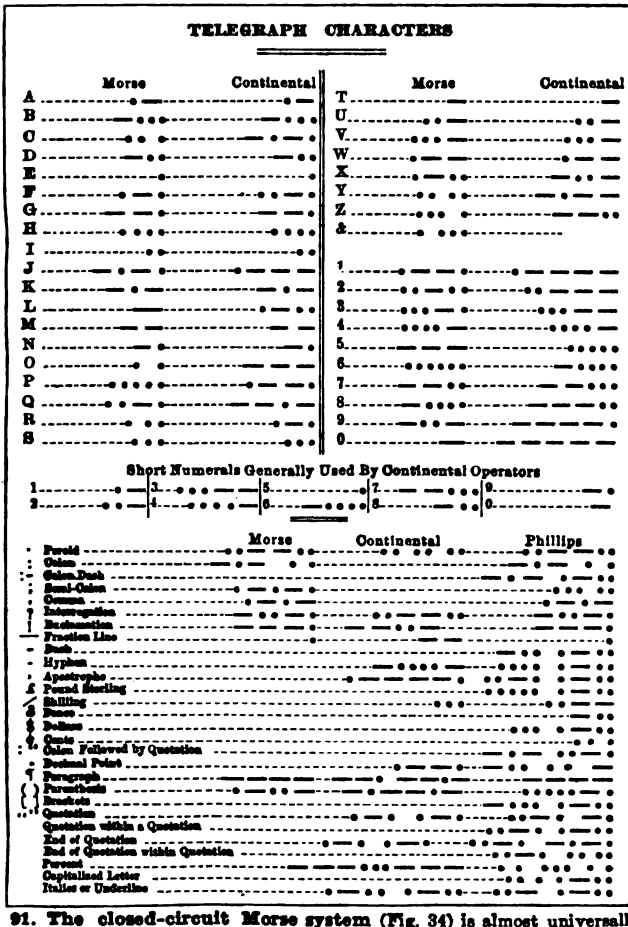
STANDARD MANUAL TELEGRAPH SYSTEMS

88. The manual Morse telegraph system comprises a means of transmitting combinations of short and long impulses or signals over an electrical circuit joining two or more points; the transmitting mechanism consists of a hand-operated key and the receiver consists essentially of an electromagnet with a sound-amplifying device for audibly registering the signals, which are read by ear. The combinations of long and short signals are so arranged as to form a code or alphabet, of which there are two in common use; the **Morse alphabet** is universally employed in American practice (except wireless) and the **Continental alphabet** in Europe.

89. Morse characters. The basic element of the Morse alphabet is the **dot;** a **dash** is equal in duration to three dots; the **space** between the elements of a letter equals one dot; between complete letters of a word, three dots; between words, six dots. The 26-letter American Morse alphabet has 77 elements, or an average of 2.96 elements per letter; the Continental alphabet of 26 letters has 82 elements, or 3.15 elements per letter. The average five-letter word has 36.7 elements or dot-equivalents in American Morse. A speed of 25 words per min. in American Morse corresponds to an average of 370 signals per min., or between 6 and 7 per sec.

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20. Morse and Continental Alphabets.*



21. The closed-circuit Morse system (Fig. 34) is almost universally employed in this country, except for installations of automatic printing systems, some of which employ multiplex or high-speed transmission. The ordinary closed-circuit Morse system, worked simplex, duplex, or quadruplex, is the only one here treated in any detail.

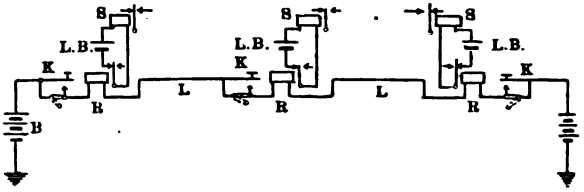
22. The open-circuit Morse system is employed extensively in England and on the Continent, but has never found favor in American

* Appendix "*C*" from McNicol's, "American Telegraph Practice," page 492.

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practice. For the details of this system consult the references on telegraphy given in the Bibliography, Par. 263.

93. Simplex or single working is indicated in Fig. 34, which shows the theory of a circuit with two terminals and one intermediate station. In this system but one message can be sent at one time. But one line wire is required, with earth return. The station equipment consists of a main-line relay, a local sounder and battery, and a sending key. There are but two main-line batteries, one at each terminal; these batteries or sources of e.m.f. should be of equal voltage for best results, and the terminals should have substantially equal resistances. The terminal resistances should also be as small as practicable.



B.—Main-line batteries.
K.—Keys.
R.—Main-line relays.
S.—Local sounders.
L.B.—Local batteries
L.—Line.

FIG. 34.—Closed-circuit Morse system.

94. Sources of energy for telegraph working are usually one of four types, viz., gravity batteries, dry batteries, storage batteries, or generators. For details on batteries, see Sec. 20; generators, Sec. 8; dynamotors, Sec. 9. Gravity cells are now employed only for small installations, as a rule, working a few wires; dry cells have been employed to a limited extent, for working individual wires; the general objections to such batteries are high internal resistance and high cost of maintenance. Storage batteries have been used in large installations and are considered fairly satisfactory. Generators or dynamotors are coming into quite general use wherever a source of cheap primary energy is available. Any number of lines can be operated from one machine of adequate output.

95. The main-line relay consists merely of a double-pole electromagnet with a light armature and retractile spring, provided with suitable adjustments and arranged with local contacts for closing the circuit of a local sounder. The standard main-line relay is wound for 150 ohms of resistance and should be operated with currents of 40 to 50 milliamperes. Relays for intermediate offices on way circuits are generally wound for 350 ohms, in order to reduce the total line-resistance and improve the operating efficiency; the operating current should be from 60 to 70 milliamperes or more. Pony relays for short lines are usually wound for 20 ohms. Special relays are wound as high as 300 ohms.

96. The proper relay adjustment depends upon the condition of the line. In clear weather, with high insulation, the air gap may be small and the spring tension high; in wet weather, with low insulation, the air-gap should be lengthened and the spring tension reduced, because the margin of operating current caused by the opening and closing of a distant key, is much reduced. An ordinary 150-ohm relay, operating on 0.050 amp., will not release at commercial speed on much more than 75 per cent. of the normal current, or at about 0.0375 amp. The armature play should be as confined as possible, in order to shorten the stroke.

97. Sounders are necessary because the ordinary line relay has insufficient power to make audible signals for easy reading of Morse characters. Sounders are usually wound for 4 ohms or 20 ohms resistance; in the latter case the sounder may practically serve in place of a pony relay for short lines.

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98. The operating currents required in closed-circuit Morse working vary according to the system of working and the sensitiveness of the relays. The usual current with 150-ohm relays, line-circuit closed, is about 0.040 to 0.050 amp.; with 35-ohm relays, 0.060 to 0.075 amp.; for 20-ohm pony relays, about 0.100 amp.; for local sounders, 0.100 to 0.250 amp.

99. The polar duplex is illustrated in theory in Fig. 35, which shows but one terminal of the line, since the other is identical. The polar relay, as its name indicates, is polarized, and responds to currents in one direction but not the other. In order that the armature may be under a slight normal attraction when no signals are passing, it is given a slight bias, or so adjusted that it is nearer one pole-piece, than the other. The polar relay, being differentially wound, is neutral to outgoing currents from the home key, if the artificial and the real line-circuits are electrically balanced. When the distant key is closed the line current in the upper limb of the polar relay becomes (theoretically, with a perfectly insulated line) double that in the lower limb and actuates the local sounder; if the home key is next closed, the relay is not affected. If the home key is closed, while the distant key is normal, the home relay will also be unaffected, as can be seen from consideration of the relative strengths and directions of the currents in the two limbs.

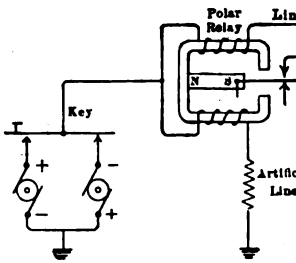


FIG. 35.—Theory of differential polar duplex.

100. The bridge duplex is shown theoretically in Fig. 36, where R_1R_2 are two equal resistances, or equal windings of an impedance coil. The relay is a plain non-polarized type. The compensating resistance should be equal to the internal resistance of the battery, in order not to upset the adjustment of the artificial line.

101. The bridge polar duplex* is similar to Fig. 36, except that the battery and key are displaced by the generators and key in Fig. 35, and a polar relay is required.

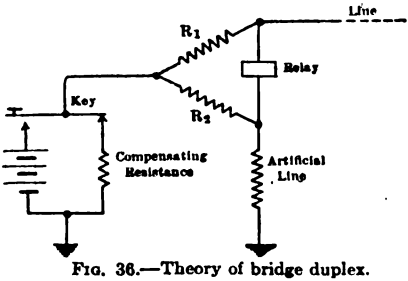


FIG. 36.—Theory of bridge duplex.

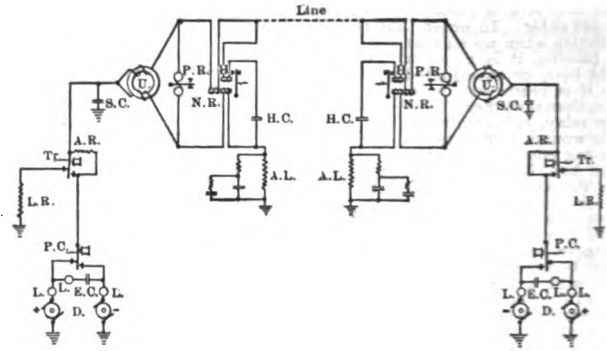
102. The bridge quadruplex of the Western Union type developed by Athearn† is shown in theory in Fig. 37. The function of the holding coil *H* on the neutral relay is to hold down the armature of the relay during reversals on the polar side. The extra current condenser *E.C.* has a capacitance of about 0.25 mf. and is in series with a 20-ohm resistor. The impedance coils *U* have a total resistance of 1,000 ohms, or 500 ohms per side. The operating currents are about 0.020 amp. for the polar side and 0.060 for the neutral or common side. This type of quad is very efficient and less subject to interference from inductive disturbances on the line than the differential quad.

* *Telegraph and Telephone Age*, Dec. 1, 1912, p. 802 and Dec. 16, 1912, p. 835.

† *Telegraph and Telephone Age*, Mar. 16, 1911, p. 226: also see issue of Nov. 1, 1910, p. 722.

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The polar side is virtually a bridge polar duplex, working on current reversals, and the neutral side is a Stearns duplex, working on a current margin of about one to three. The Field key system used with the transmitter for the neutral or common side is next described. The pole-changer and the transmitter for the common side are both worked from separate keys in local circuits.



D.—Dynamos.
P.C.—Polechanger.
Tr.—Transmitter
A.R.—Added Resistance.
L.R.—Leak resistance
S.C.—Spark condenser.
L.—Resistance lamps.
U.—Retardation coil.
P.R.—Polar Relay.
N.R.—Neutral Relay
H.C.—Holding condenser.
H.—Holding coil on N.R.
A.L.—Artificial line.
E.C.—"Extra current" condenser.

FIG. 37.—Theoretical circuits of Athearn (Western Union) improved quadruplex.

103. The Field key system is very useful in quadruplex working where generators or dynamotors are employed as sources of e.m.f. This system requires but one source of e.m.f. at each terminal, giving the full voltage required for the neutral side. The circuits of the system are given in Fig. 38, which shows the transmitter for the neutral side, with the pole-changing transmitter omitted; L is the protective resistor, and A and B are respectively the "added" resistance and the "leak resistance." If the ratio of long to short voltage, for neutral working, is n, the values of A and B are:

$$A = L(n-1) \text{ and } B = L\left(\frac{n}{n-1}\right) \text{ (ohms)} \quad (1)$$

where all resistances are expressed in ohms.

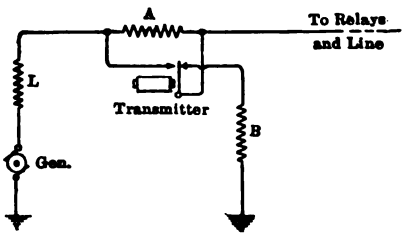


FIG. 38.—Circuits of the Field key system.

104. The Postal improved quadruplex is of the differential type, but is equipped with a special system of condensive shunts. For a description of the system, see Skirrow, J. F. "Postal-Telegraph Cable Company's Improved Multiplex Apparatus," *Telegraph and Telephone Age*, Dec. 1, 1912, p. 761.

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105. The artificial line must be adjustable, both in resistance and capacitance, in order to establish readily a balance with the real line. When adjusting for a balance the distant battery or generator should be cut out, and a connection made to ground in its place, through an equivalent resistance.

106. Single-line repeaters designed to repeat signals from one Morse circuit to another, with single working, are of various types, including the Milliken, Toye, Weiny-Phillips, Ghegan, Atkinson, Neilson, Horton, d'Humy and others. Only one of these types will be shown; for descriptions of others see the references in Par. **263**. Every repeater embraces, for each line, a receiving relay, a transmitter and a holding device; these elements, in duplicate, are common to every type. The principal differences among the various types relate to the form of holding device.

107. The Milliken single-line repeater is shown in Fig. 39, where *RR'* are the main-line relays, *TT'* are the transmitters, and *EM*, *EM'* are the extra magnets or holding devices. When the circuit opens on the west, relay *R* is released, opening the local circuit of transmitter *T* and in turn discon-

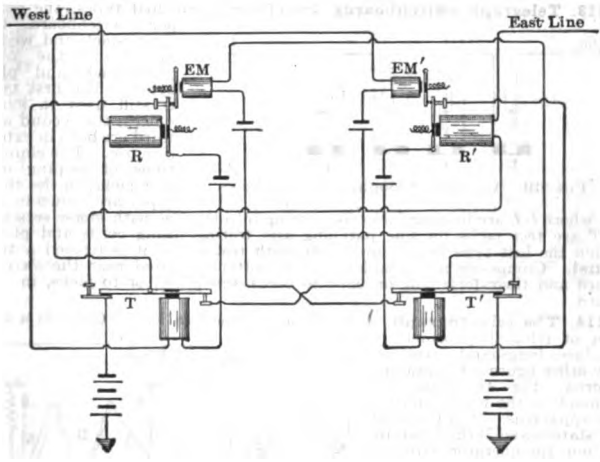


FIG. 39.—Circuits of the Milliken single-line repeater.

necting the battery of the line east; simultaneously the magnet *EM'* is released and its armature falls back on the armature of relay *R'*, holding it closed and thus protecting the transmitter *T'*. The other operations will be evident from this description and the circuits in Fig. 39.

108. Duplex and quadruplex repeaters* are very simple, it being necessary only to place the pole-changer of the east line under control of the polar relay on the west line, and the transmitter (common side) of the east line under control of the neutral relay on the west line, with corresponding connections for working from east to west.

109. Half-set repeaters consist of one relay and one transmitter for connecting a duplexed line with a single line, or one side of a quad with a single line.

110. The phantoplex is a system for superimposing an alternating-current telegraph on an ordinary single, duplex or quadruplex circuit.† It

* "Western Union Bridge Duplex." *Telegraph and Telephone Age;* Jan. 16, 1913, p. 54; Feb. 1, 1913, p. 84.

† McNicol, D. "American Telegraph Practice;" McGraw-Hill Book Co., Inc., New York, 1913; Chap. XIX.

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operates at from 60 to 120 cycles, being linked to the line through series transformers. The phantoplex can be duplexed, and, when superimposed on a polar duplex, provides a quad. It has been used to some extent by the Postal Telegraph-Cable Co. The phantoplex should not be used on composited telephone circuits, and may give rise to inductive disturbances in parallel telephone circuits.

111. The phonoplex is a system for superimposing a high-frequency alternating-current telegraph on a morse circuit of the usual type.*

112. Telegraphing to moving trains has been successfully accomplished by means of inductively related circuits situated on the trains and parallel to the track. The Edison system of inductive telegraphy from a stationary wire along the road, to moving trains, operated by electrostatic induction; the Phelps system operated by electromagnetic induction. The most successful method of communication for such service, however, is wireless or radiotelegraphy (Sec. 21), which has been given extensive trials on the Delaware, Lackawanna and Western Railroad.

113. Telegraph switchboards are of three principal types, the early peg switchboard, the spring-jack and wedge type, and the telephone-jack and plug type. The first type is still used in small offices; the second and third are both in extensive use. The connections of looping and test jacks, in the third type, are shown in Fig 40, where *L L* are looping jacks for cutting into the line with morse sets and *T T* are test jacks for line patching and testing, using cords and plugs. When the last type is equipped only with test jacks, it is termed a **test panel**. Composite and simplex sets are often mounted near the switchboard and their terminals brought to cords and plugs, or to jacks, in the board.

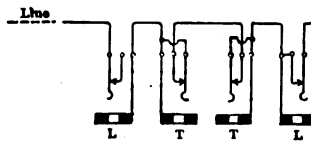


FIG. 40.—Circuits of looping and test jacks.

114. The telautograph, an invention of the late Elisha Gray, is a system of telegraphy which reproduces long-hand writing or any other figures or characters desired. Fig 41 shows the principle of the writing part of the apparatus. A is the sending station and B the receiving station; the operator writes on a tablet (not shown in sketch), with pencil 1, which is so linked to arms 2 of rheostats 3, that the motions are split into two components and the resistances varied in proportion to these components. Each of the rheostats is situated in a separate line-circuit, at the receiving end of which is connected a magnet coil, 4, the coil being located in magnetic field of constant value. Variations in the current value in coils 4 cause corresponding variations in the pull acting between the coil and the constant field; coils 4 are connected mechanically to arms 5, the pull being opposed by springs 6. It is easy to see that pen-point 7 will follow the movements of pencil 1 and reproduce any motions which the latter may make. This system requires two line wires, in order to transmit two independent currents of varying strength.

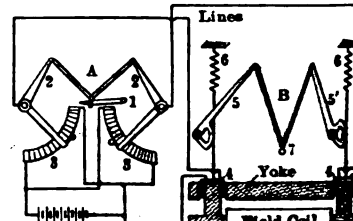


FIG. 41.—Theory of the telautograph.

* Maver, Wm. Jr., "American Telegraphy and the Encyclopedia of the Telegraph," New York, 1909.

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The telautograph is extensively used in railway terminals, hotels, clubs, factories, etc., for local intercommunication. See Dixon, J. "The Telautograph;" *Trans.* A. I. E. E., 1904, Vol. XXIII, p. 645.

SIMPLEX AND COMPOSITE SETS

115. Simultaneous telephony and telegraphy over the same wires is obtained commercially by means of two different systems, known as the simplex and the composite.

116. Simplex sets operate on precisely the theory of a grounded or half phantom, employing either an impedance coil or a repeating coil. The telephone circuit corresponds to the side circuit of the half-phantom (Par. **85**) and the telegraph circuit corresponds to the phantom circuit. An impedance-coil simplex set is illustrated in theory in Fig. 42. Battery, relay and key are connected to the morse leg in the familiar manner. This system permits only one telegraph circuit (with earth return) to be derived from a metallic pair or physical circuit.

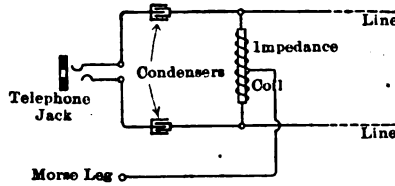


FIG. 42.—Impedance-coil type of simplex set.

117. Composite sets permit the use of both sides of a metallic pair for telegraphy, thus deriving two telegraph circuits, or one circuit per wire, with earth return. A composite set for a single-wire grounded telephone circuit is indicated in theory in Fig. 43. The combination of 6-mf. condenser and 50-ohm impedance coil is for the purpose of retarding the rise of current and e.m.f. in the line when the key is closed. Without such retardation the very sharp rise of current and e.m.f. would produce a marked sound or click in the telephone receiver and make communication impossible during the

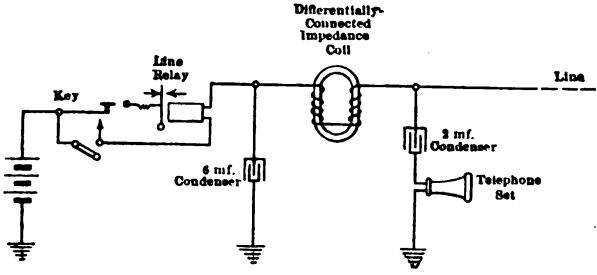


FIG. 43.—Composite set for grounded lines.

sending of telegraph signals. The effect of the coil and condenser, is so to round off the morse impulses that they are almost entirely inaudible in the telephone receiver, and when heard are usually so soft as to constitute practically no impediment to speech transmission. The size of the condenser is usually regulated to some extent by the battery voltage; 6 mf. is usually adequate for any voltage up to 125 volts at each terminal. The 2-mf. condenser is obviously for the purpose of preventing the morse currents from shunting or leaking to ground through the telephone set; a condenser of 1 mf. is sometimes used. When the impedance coil is connected serially for maximum impedance, instead of differentially as shown, the 6-mf. condenser can be replaced by a considerably smaller capacitance, or about 1 mf. The coil and condenser combination always retards the speed of morse signalling

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to some extent, although the drag is not usually serious unless the coil impedance and the capacitance are too large.

A full composite set for metallic circuits is indicated in Fig. 44. This set is comprised of two sets of the type in Fig. 43, with the addition of the coils *ee* and condensers *dd*. The 50-ohm differential coils *aa*, the 6-mf. condensers *bb* and the 2-mf. condensers *cc* perform the same functions as in the half-set in Fig. 43. The 2-mf. condensers *dd* and the serially connected 30-ohm coils *ee* are for the purpose of shunting to ground the Morse impulses passing through the condensers *cc*, which otherwise would flow through the telephone circuit and result in cross-writing between the two morse legs.

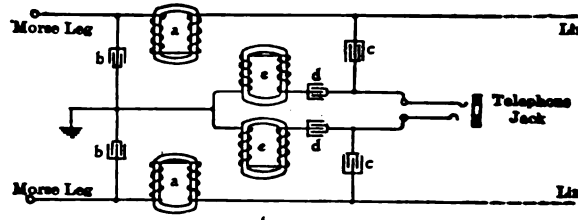


FIG. 44.—Full composite set for metallic circuits.

118. Duplex working through composite sets requires the connection of a dummy composite set in the artificial line at each terminal, in order to establish a balance with the sets in the main line. It is also feasible to connect a grounded shunt condenser and serial impedance coil between the pole-changing transmitter and the polar relay, in order to further subdue the sharpness of the impulses when transmitting morse.

119. Composite ringers. It is not permissible to signal over composited telephone circuits with the usual 16-cycle ringing current, since it will chatter the morse relays. A high-frequency ringing system is in use which operates with relatively weak currents and does not interfere with simultaneous morse transmission.*

DISPATCHING AND PATROL SYSTEMS

120. Train dispatching systems on steam railroads were formerly operated by Morse telegraph exclusively, but the telephone has extensively superseded the telegraph during the last 12 to 15 years. Dispatching systems on electric interurban railways have been operated by telephone almost without exception since the earliest days of such systems. A train-dispatching system comprises in brief a master sending or transmitting station, with means for selectively signalling all other stations, a line circuit, and a plurality of way stations equipped primarily for receiving. Dispatching systems vary in detail, but nearly all embrace the same fundamental features.† Dispatching equipment is manufactured by nearly all of the leading makers of telephone equipment, and the details of each system are too extensive to reproduce here. Only the leading features will be described.

121. Direct-current selector systems. The direct-current type of selector, one of which is shown schematically in Fig. 45, represents the earliest form of selective calling device employed in dispatching systems and is still in extensive use. Normally the battery circuits are open. The automatic calling-key is operated by clockwork, there being a separate key for calling each station. The particular key shown will send a combination of im-

* Kissel, N. C. "The Composite Ringer;" *Telegraph and Telephone Age*, May 1, 1910, p. 318.

† Brown, G. "Some Recent Developments in Railway Telephony;" *Trans. Amer. Inst. of Elec. Eng.*, 1911, Vol. XXX, p. 1007.

Clapp, M. H. "A Comparison of the Telephone with the Telegraph as a Means of Communication in Steam Railroad Operation;" *Proc. A. I. E. E.* Mar., 1914.

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pulses to line represented by 3–1–2–1. The object of the retardation coils and condensers at the dispatcher's station is to make the signals inaudible in the telephone receivers which may be connected to line (Par. 117). Each way station is equipped with retardation coils to minimise the shunting

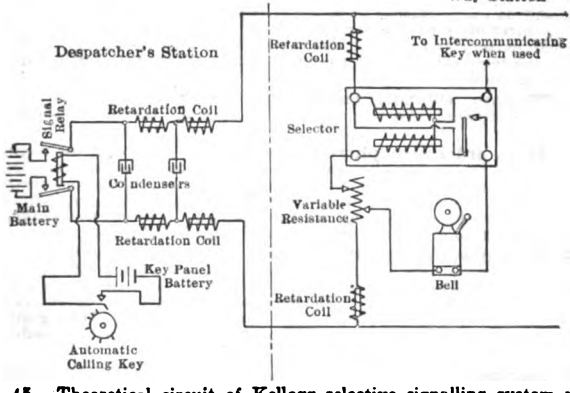


FIG. 45.—Theoretical circuit of Kellogg selective signalling system using Gill selector, for train dispatching.

effect on voice currents, and also has an adjustable (tapering) resistance designed to equalise the line currents in all the selectors to about 0.008 amp. each. A **Gill selector** is employed at each station, which is so arranged that a combination of impulses, with intermediate intervals, will rotate a wheel and at a certain point in its travel close a local bell circuit. The bell may be operated by local battery or from the main line, and the dispatcher receives a signal in his own receiver which gives a positive indication that the bell is ringing. The dispatcher can also prolong the ringing as long as he desires, by means of a special key.

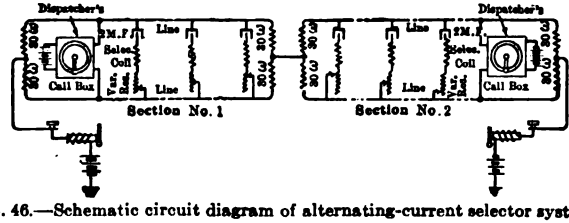


FIG. 46.—Schematic circuit diagram of alternating-current selector system.

122. Alternating-current selector systems are the latest development and possess several advantages over the direct-current system. The way-station selector is a simple polarised mechanism, similar in principle to a polarised bell, equipped with a step-by-step device which actuates a rotary circuit-closing member and controls the local bell circuit. Each selector is adjusted to operate on a predetermined number of electrical impulses that are sent out from the calling station by means of an appropriate selector key. The usual answer-back feature is also provided. Alternating-current selectors permit the introduction of condensers in the bridging circuits at the way stations, operate on less energy and as a whole have greater range and flexibility than the direct-current type. The tapering resistance is also dis-

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penses with in certain makes of equipment. Fig. 46 shows schematically the circuits of one make of equipment of this type, equipped with a superimposed simplex telegraph for through service.

123. Intercommunicating features can be provided in dispatching systems if desired. One method is to install the complete master station equipment at every station from which it is desired to call other stations. Another method is to simplex the line at the dispatcher's office, with a grounded battery and a relay, and install special grounding keys at each station; the relay can be used to control the selective transmitter and thus call any station desired.

124. Message telephone circuits can also be equipped with selective signalling equipment like that described above for telephone dispatching circuits.

125. Train order semaphore signals can be controlled by means of selective signalling systems like those employed in train dispatching circuits, so that the dispatcher may set semaphore signals (Sec. 16) against oncoming trains at any one or more of numerous locations along the permanent way. There are several such systems on the market, including the Blake, the Stromberg-Carlson and the Hall Switch and Signal Co.'s systems.

126. The railway composite system is designed for operation on ordinary morse telegraph circuits and comprises a grounded composite system for simultaneous telephony and telegraphy (Par. 117). The telephone sets are usually of the bridging type. High-frequency alternating current is used for signalling, with a howler for announcing incoming calls. These grounded circuits are so noisy that it is necessary to connect a low-resistance inductive shunt across the receiver terminals.

127. Iron-box sets of the weather-proof type are often employed for mounting on poles or other out-door structures. The line circuit is often arranged to be under control of switches automatically closed by the operation of opening the door; the set is totally disconnected when the door is closed. In some instances these sets are protected with insulating transformers or repeating coils mounted inside of the case.

128. Sets installed in booths are quite common practice on interurban electric roads. The booths are usually constructed of wood and pad-locked so as to be accessible to trainmen or employees only. These booths are generally located at turnouts or sidings. The equipment consists of a wall set, line switch, protector, and train register. The line switch is often arranged so that it is automatically operated by the door of the booth.

129. Portable sets are made for numerous purposes, and are frequently very useful in emergencies. Semi-portable sets are carried extensively on trains for emergency use, connection with the telephone line being secured by the use of a fish pole or a jack box and plug. Such sets weigh from 15 to 30 lb. The transmitter and the receiver are often mounted on a combination handle, so that both can be held in position for use by one hand.

130. Jack boxes for connection with portable train sets are usually installed at intervals of ½ mile along the right-of-way, mounted on the poles and connected (bridged) to the line circuit through protectors. The portable sets are equipped with suitable extension cords and plugs.

131. Line poles or fish poles for connecting portable sets with the wires on a pole line are made of hickory or maple, in sections about 6 ft. long, with telescoping or socket joints. Flexible cords are also provided, and suitable connectors for making contact with the wires.

132. Linemens' test sets formerly consisted merely of a hand generator, a polarised buzzer and a telephone receiver, with a switch for signalling and talking. The modern sets are somewhat more elaborately equipped; one manufacturer produces a set weighing 8 lb., equipped with 2-bar generator, buzzer, transmitter, receiver and cord, induction coil, flashlight dry-battery and switch, the whole set being capable of ringing through a 2,500-ohm non-inductive resistance. In another type of set a 1,000-ohm bell is used in place of the buzzer, and a condenser in series with the talking circuit if needed.

133. Load dispatching is a comparatively modern development and involves the use of similar means of communication between a main generating station and the substations in a comprehensive electrical distribution system

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or network, for directing the distribution of electrical energy, that have become familiar in railroad practice for directing train movements. The load dispatcher is situated at the main switching centre and directs the switching operations on the whole system, including all the substations and any auxiliary generating stations; he also directs the starting and stopping of generating units, in response to changes in the system demand. The telephone equipment for such service is not as a whole distinguished by any unusual or radical features, and needs no further elaboration. It is quite essential, in electric trunk line operation, to provide ready communication between the train dispatchers and the load dispatcher.

134. Patrol systems may be defined as embracing telephone lines extending along routes covered by patrolmen or inspectors, provided with means at intervals of ½ mile or so for connecting portable sets and establishing temporary communication with headquarters. In the place of portable sets, there may be booths or boxes at fixed locations, with telephones therein. Patrol systems are in use along railroad rights of way and along the routes of transmission and distribution lines. In the case of high-tension lines, it is desirable where possible to have the telephone line on separate poles or supports at some distance away; this not only reduces the induction on the telephone line, but also renders it safer and tends to make it more dependable in emergencies, when it is most needed.

FIRE AND POLICE ALARM SYSTEMS

135. Fire alarm systems consist essentially of signal boxes distributed over the area to be protected, a series line circuit looping through the boxes,

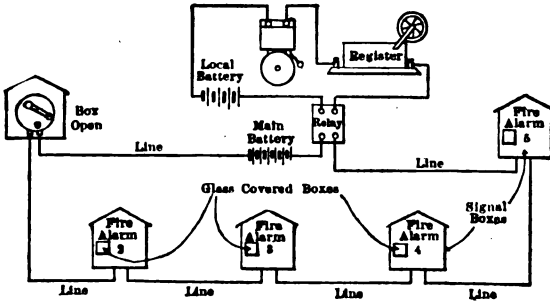


FIG. 47.—Elements of a small fire-alarm system.

and a central station at the engine house or fire headquarters where signals from the boxes will be registered as received and the alarm given. The simple elements of such a system are shown in Fig. 47. Lack of space prevents more than brief description of the characteristic details; further information should be sought in the references given in the bibliography, Par. **263**.

136. The line circuit is normally closed, as shown in Fig. 48. If an alarm is turned in at signal box 12, the circuit will be interrupted once, then after a pause, twice, this signal being repeated each time the wheel revolves; and each time the line relay R becomes de-energized, the bell relay B causes the bell to be struck once.

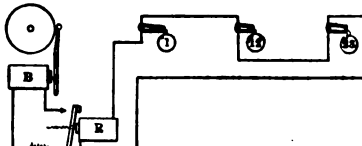


FIG. 48.—Elementary line circuit.

137. Non-interfering box. If two or more alarms should be turned in simultaneously on the same line, they would interfere with each other and

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the bell signals would be confused. In order to avoid such occurrences, the fire-alarm boxes are each provided with non-interfering equipment, so that two simultaneous alarms would be transmitted in sequence, without interference.

138. The central station equipment comprises the receiving mechanism for indicating the particular box from which an alarm is sent; the register for keeping record of the alarms received, as to date, time and location; the visual and audible alarms; and in some cases there are included means for repeating the alarms to other points. Small systems having but one or two circuits are frequently automatic in their operation; but large systems having many lines, as in cities, are usually non-automatic and require attendance in order that alarms received at headquarters may be transmitted to the engine houses. Large systems are usually provided, however, with numerous automatic or semi-automatic features, which may be switched in or out of service at will. Many details are described in Maver's "American Telegraphy."

139. Thermostat systems. Factory buildings are very often equipped with automatic fire alarms, which can either be used to give an alarm in the central office of the works or to communicate it to the public fire department. Such alarms are actuated by some form of thermostat, which closes a circuit when a given temperature is reached.

140. Police alarm systems are similar in a general way to fire-alarm systems, but usually employ the telephone as an auxiliary, for direct communication. Patrolmen on beat turn in signals from the boxes, in rotation, as they reach them. These signals are recorded by the register, at police headquarters or the local police station, showing the date, time and box number. For details see Maver's "American Telegraphy."

141. Flash-lamp police systems are now employed to a considerable extent for sending out calls from headquarters to patrolmen on beat. This system employs a lamp signal, usually red, at each patrol box; the signals are under control from headquarters and code signals can be arranged in various ways to convey different orders. Sometimes audible signals or bells are employed in addition to the visual signals.

TELEPHONE CABLES

142. Conductors for telephone cables are almost without exception made of annealed copper wire; this is always tinned if it is to be insulated with rubber or any material containing ingredients tending to corrode copper.

143. Insulation is usually composed of dry paper tape wrapped spirally about each conductor. In the case of single wrapping, the paper is overlapped so as to provide double thickness; when double wrapping is employed, the second layer is applied in reverse direction with respect to the first.

Other insulations are employed, such as cotton, silk, wool and enamel for interior cables, and impregnated paper, rubber compounds and gutta percha for submarine cables.

144. Twisted pairs are formed by twisting together two paper-insulated conductors, the length of one complete twist ranging as follows: 3 in. for No. 22 A.W.G., 3 in. to 5 in. for No. 19 and No. 16, 4 in. to 6 in. for No. 13 and 6 in. to 8 in. for No. 10 A.W.G. The purpose of twisting the pairs is to prevent cross-talk and secure electrical balance of the two conductors composing a metallic circuit.

145. Laying up the core. The twisted pairs are laid up in consecutive spiral layers, with adjacent layers spiralled in reverse directions (concentric lay). The numbers of pairs composing the layers are as follows, in progressive order: 1, 6, 12, 18, 24, 30, 36, 42, etc. This rule of course applies only where the pairs are all of the same size.

146. Cable sheaths were formerly made almost universally of a lead-tin alloy, with 97 per cent. of lead and 3 per cent. of tin. The purpose of the tin is to give increased strength and hardness to the lead. A modern development is the use of a lead-antimony alloy containing about 1 per cent. of antimony, which is said to be less susceptible to injury or cracking from vibration, and effects a small saving in cost.

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147. Aerial and underground lead-covered paper-insulated cable
(Western Electric Co.)

No of pairs	No. 22 A.W.G.			No. 19 A.W.G.		
	Thickness of sheath (in.)	Approx. weight per ft. (lb.)	Convenient no. of feet on reel	Thickness of sheath (in.)	Approx. weight per ft. (lb.)	Convenient no. of feet on reel
5	1/64	0.530	2500	1/64	0.640	2500
10	1/64	0.640	2500	1/64	0.850	2500
15	1/64	0.745	2500	1/64	0.970	2500
20	1/64	0.849	2600	1/64	1.138	2000
25	1/64	0.970	2500	1/64	1.264	2000
30	1/64	1.019	2500	1/64	1.390	1500
40	1/64	1.189	2000	1/64	1.643	1500
50	1/64	1.319	2000	1/64	1.995	1500
55	1/64	1.370	1500	1/64	2.130	1200
60	1/64	1.449	1500	1/64	2.220	1200
75	1/64	1.645	1500	1/64	2.584	1200
90	1/64	1.831	1500	1/64	2.810	1200
100	1/64	2.120	1500	1/32	3.738	1000
110	1/64	2.250	1200	1/32	3.949	1000
120	1/64	2.480	1200	1/32	4.221	1000
150	1/64	2.740	1200	1/32	4.865	1000
180	1/64	3.039	1200	1/32	5.439	1000
200	1/32	4.058	1000	1/32	5.808	800
220	1/32	4.257	1000	1/32	6.168	800
240	1/32	4.474	1000	1/32	6.594	800
300	1/32	5.163	800	1/32	7.587	700
330	1/32	5.460	800			
360	1/32	5.853	800			
400	1/32	6.212	700			
440	1/32	6.654	700			
480	1/32	6.920	700			
500	1/32	7.360	500			

These cables have the following constants per mile:

	No. 22	No. 19
Average mutual capacity (mf.)	0.070	0.074
Average grounded capacity (mf.)	0.105	0.111
Insulation resistance (megohm-miles)	500	500

Lead-antimony alloy (Par. **146**) is employed for the sheaths. There is but one application of paper insulation; this is so laid on, however, as to provide two thicknesses of paper over each conductor.

148. Aerial lead-covered paper-insulated cable, is made in sizes from 5 to 400 pairs of No. 22 A.W.G. with either double or single wrapping of paper, and pure lead sheaths. Such cable has a mutual capacitance of 0.08 mf. and a grounded capacitance of 0.12 mf. per mile, with a minimum insulation resistance of 500 megohm-miles. On account of the higher capacitance it is somewhat more compact and lighter than No. 22 cable of 0.070 mf. per mile.

149. Composite cable is the term applied to cable which is made up of pairs of more than one gage or diameter, as for example, No. 22, No. 19 and No. 14 A.W.G. Such an arrangement is often economical for trunk cables where several different transmission requirements must be met.

150. Phantom circuits in cable are made possible by twisting together two similar metallic pairs, constituting a **"quad,"** and laying up such quads in reversed helical layers, after the manner of an ordinary cable. In order to economize in the use of space within the sheath, however, it is customary to add as many single pairs as space will permit.

151. Electrolysis of lead cable sheaths from stray or foreign currents is covered as a whole by the article in Sec. 16.

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PROTECTORS

152. Protection of telephone and telegraph equipment against foreign currents of a hazardous character is necessary for two purposes: first, the protection of the lives and persons of the users of the apparatus; second, the protection of the apparatus itself.

153. The general practice in protection is based on the assumption that under ordinary conditions of construction and operation it is not practicable to use protective devices which are adequate to cope with potentials or energies larger than those met in ordinary central station distribution, or say not above 4,000 volts approximately. Such devices are also counted upon to divert ordinary discharges of induced lightning, or distant strokes directly striking the line. Where the conditions of construction and operation unavoidably involve hazardous exposure to high-potential circuits of high energy, it becomes necessary to adopt stronger types of construction designed to prevent accidental contact of the two systems, or to employ more efficient protectors designed to handle such potentials and energies, or both. It is considered safe by some authorities, however, to depend upon the standard forms of protectors for exposures to circuits operating at not more than 5,000 volts, constant potential, alternating; 5,000 volts, series, alternating current; 7,500 volts, series, direct current; and 1,000 volts, railway trolleys or feeders, direct current.*

154. Standard telephone protectors, so-called, consist of fuses in series with the line, and high-potential cut-outs or lightning arresters bridged

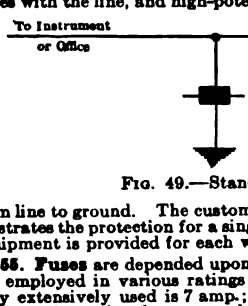


FIG. 49.—Standard telephone protector.

from line to ground. The customary arrangement is shown in Fig. 49, which illustrates the protection for a single wire. In the case of metallic circuits the equipment is provided for each wire.

155. Fuses are depended upon for protection from excessive currents and are employed in various ratings from 1 amp. to about 15 amp. A rating very extensively used is 7 amp.; ratings of 10 and 12 amp. are also used. Fuses of the enclosed type are almost invariably used, vertically mounted; the enclosing tubes are slotted to permit escape of hot gases, the slots should be turned toward the wall, and the latter protected with an asbestos mat.

156. Arresters or open-space cut-outs are manufactured in various types. Two carbon blocks separated by a perforated or slotted sheet of thin mica form one of the very common types; in some cases one of the carbon blocks is recessed and filled with fusible metal, to melt and permanently ground the line under heavy discharge. Such an arrester is usually adjusted to break down at about 350 volts continuous current; this breakdown value is, however, somewhat uncertain and not subject to close control.

A type of open-space cut-out arranged with copper or non-arcing metal blocks separated by a thin mica, is also used where there is no attendant near to keep the arresters clean, and overcomes the objectionable tendency of the carbon type to clog with carbon dust as the result of discharges in action.

157. Vacuum arresters. This type of arrester, which consists essentially of a spark-gap placed in a rarefied atmosphere, was developed for the purpose of overcoming the uncertain discharge characteristic of the open-space carbon cut-out and similar types of arresters. Among its advantages are relatively wider gap, larger electrodes, greater sensitiveness to high frequencies and less fusing and grounding of electrodes. It is also compact

* Clapp, M. H. "Protection against Lightning and High Currents for Telegraph and Telephone Equipment;" Annual *Proceedings*, Association of Railway Telegraph Supts., 1913.

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and readily mounted. Among its disadvantages are the lack of visual indication of the state of rarefaction and possible change of discharge characteristic due to volatilisation of electrodes.

158. Ground wires from arresters to earth form a most important link in the system of protection. The conductor should be not smaller than No. 14 A.W.G. and should pass by the nearest accessible route to a substantial ground plate, rod, or coil, or to a water pipe; **gas pipes should never be used** for this purpose. Too much care cannot be given to securing good electrical connection with the earth, of a substantial and reliable character.

When a wrought-iron or steel water pipe (service connection) is not available, a fairly efficient earth connection can be made by driving an iron or steel pipe or rod into the ground, in a moist location, to a depth of 5 or 6 ft. See Hayden, J. L. R. "Notes on the Resistance of Gas-pipe Grounds;" *Trans.* A. I. E. E., 1907, Vol. XXVI, p. 1209.

159. Heat coils or sneak-current arresters are, in reality, fuses of special construction, designed to overcome the unreliability of ordinary fuses for very small currents. For example, a heat coil can be constructed to operate on a current of 0.2 amp. in 30 sec., or a variety of other ratings. This device comprises a small winding of fine wire, which develops sufficient heat to melt a small piece of fusible metal and release a spring which grounds the line circuit; the resistance of the winding usually amounts to several ohms, at least. The function of heat coils is to protect telephone apparatus wound with fine wire (relays, drops, etc.), such that injury might result from foreign currents insufficient to blow the fuses. The proper location for the heat coils is between the protectors and the apparatus, but not in the talking circuit if avoidable.

160. Protective or insulating transformers are employed to protect telephone sets, switchboards or terminals connected to lines which are exposed in a hazardous manner to high-tension high-energy transmission lines, such as those erected on the same poles or structures with a transmission circuit. An insulating transformer of this character* made by one of the leading manufacturers is built to withstand a 25,000-volt test between windings for 1 min., and requires a magnetising current equal to about half the current taken by a 1,000-ohm polarised bell. The transformer is mounted in a weatherproof case for out-door mounting; the casing should always be thoroughly grounded. It should be observed that such transformers introduce additional losses in both transmission and ringing, which should be taken into account in arranging circuit layouts.

161. Special protectors are usually employed with these insulating transformers, located between the line and the transformer. The protector consists of extra long fuses in the line circuit, with spark-gaps bridged to ground; sometimes the fuses are so mounted as to be integral with an air-break disconnecting switch. See Sec. 11.

162. Insulating stools are often used in conjunction with telephones connected to hazardously exposed lines, as in the case of patrol circuits on transmission lines, so that the attendants may be thoroughly insulated from earth while telephoning. An ordinary four-legged hardwood stool, with the legs inserted in inverted porcelain line insulators, will serve very well. **Insulating mats** are sometimes used, in dry interior locations, in place of stools, but in general are not as efficacious.

163. Extra insulation of telephone sets used in connection with hazardously exposed lines is very desirable. Exposed terminals or connections and uninsulated exposed parts should be particularly avoided in selecting equipment for such service. The hook switch should also be very thoroughly insulated.

CROSS-TALK AND INDUCTIVE DISTURBANCES

164. Induction between parallel aerial wires is due to a combination of electrostatic and electromagnetic induction. Such induction is the cause not only of cross-talk between parallel aerial telephone circuits, but also the inductive disturbances in aerial telephone lines situated in parallel exposure to aerial distribution circuits (Sec. 12) or high-tension transmission circuits (Sec. 11). The general means of eliminating such induction is by interchanging or transposing the wires of each circuit at suitable locations, in

* "Insulating Transformer for Telephone Lines;" *Telephony*, June 5, 1909, Vol. XVII, p. 666.

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accordance with a predetermined system. In severe cases it is necessary to resort to further measures of protection. The subject has been treated at considerable length in different papers, a short bibliography of which is given below.*

165. Cross-talk between parallel grounded circuits cannot be eliminated by transposition because it is physically impossible to transpose a circuit consisting of only one wire, except by inserting repeating coils and this method has never developed into a practical system.

166. Cross-talk between parallel metallic circuits can be eliminated by a system of **transpositions**, as shown in Fig. 50.

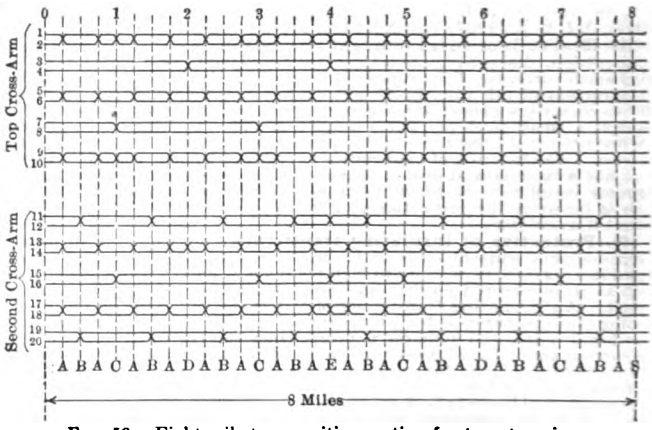


FIG. 50.—Eight mile transposition section for twenty wires.

167. A typical transposition system is shown in Fig. 50, which illustrates an 8-mile section for 20 wires or 10 circuits. This section comprises a unit which is applied successively, and the last section, if not exactly 8 miles, is taken care of by stretching or shortening the unit section to suit the case.

168. Phantom circuits impose additional transposition requirements. Each side circuit must be transposed, or the phantom will be entirely inopera-

* Fowle, F. F. "The Transposition of Electrical Conductors;" *Trans.* A. I. E. E., Vol. XXIII, 1904, p. 659. "The Transposition of Farmer Lines;" *American Telephone Journal* (now *Telephony*), Vol. XVII, May 2, 1908, pp. 382 to 384. "Making Field Reports on Inductive Interference;" *Telephony*, Vol. LXI, Sept. 2, 1911, pp. 275 to 278.

Cohen, L. "Inductive Disturbances in Telephone Lines;" *Trans.* A. I. E. E., Vol. XXVI, 1907, pp. 1155 to 1167.

Taylor, J. B. "Telegraph and Telephone Systems as Affected by Alternating-current Lines;" *Trans.* A. I. E. E., Vol. XXVIII, 1909, pp. 1169 to 1215.

Howe, P. J. "Inductive Disturbances as Affecting Telephone and Telegraph Lines;" Annual Proceedings, Association of Railway Telegraph Supts., 1913.

Report of the Engineering Data Sub-Committee; *Proc.* A. I. E. E., Oct., 1914, pp. 1447–1523.

Report of the California Joint Committee on Inductive Interference R. R. Comm. of California, 1916.

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ive. **The phantom itself must be transposed, with respect both to its side circuits and to other physical and phantom circuits.**

169. Phantom transpositions make it necessary to modify the details n Fig. 50 quite materially; changes are necessary at one-half the total number f transposition poles and only the "A" poles remain as they were. An -mile section, arranged for phantom circuits, is given in Fig. 51. It is lso feasible to transpose pairs 5–6 and 15–16 to make a fifth phantom ircuit. A more-efficient type of section having 64 transposition points, nstead of 32, is given in the "Report of the California Joint Committee on nductive Interference."

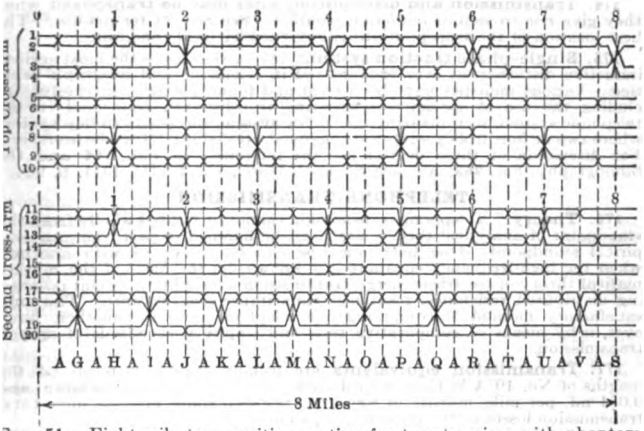


Fig. 51.—Eight-mile transposition section for twenty wires with phantom circuits.

170. Balancing coils, Fig. 52, are sometimes employed to improve the balance of metallic circuits and diminish the intensity of inductive interferences rom high-energy circuits. Such coils interfere, however, with phantom, composite or simplex operation, unless installed in the drop side or leg.

171. Drainage coils, Fig. 53, are useful in preventing excessive rise of potential on telephone lines from heavy inductive disturbances caused by parallel high-tension high-energy circuits. The installation of these coils at intervals along the circuit establishes local circuits through

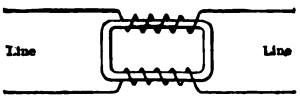


Fig. 52.—Balancing coil for metallic circuit.

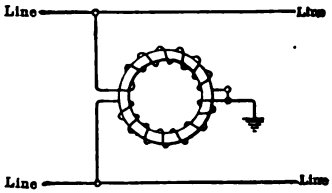


Fig. 53.—Drainage coil for metallic circuit.

earth for the flow of induced currents and thus prevents the cumulative rise of potential which otherwise might occur.

172. Inductive disturbances may be minimized by certain arrangement of phase wires, as indicated in the "Report of the California Joint Committee on Inductive Interference." The phase wires constituting any individual circuit should be grouped as close to each other as feasible. Series

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circuits should be laid out on the closed-loop system (Sec. 12) and in some cases the lamps should be connected alternately in each side of the loop, to maintain electrostatic balance.

173. Special transpositions for the elimination of foreign inductive are usually effective, but frequently require rearrangement of the whole transposition system within the section of exposure and sometimes for a distance beyond. The general principles governing the location of such transpositions have been covered in the author's paper, "Transposition of Electrical Conductors," *Trans.* A. I. E. E., Vol. XXIII, 1904, *p.* 659, and also in the California Joint Report before mentioned.

174. Transmission and distribution lines may be transposed when they give rise to serious inductive troubles. See Sec. 11 for details. The best location of the transpositions is governed by local conditions.

175. Single-phase traction systems have given rise to the most serious inductive disturbances ever encountered in telephone and telegraph practice. Various remedies have been tried and found partially successful, including the use of special compensating transformers, connected in the telephone system, sectionalising the trolley system, three-wire trolley system where two or four trolley wires are employed, special track transformers, etc. For discussion of these devices see the references in Par. **164** and the bibliography, Par. **263**; also see *Electrical World*, Vol. LXIII, 1914, p. 984.

TELEPHONE TRANSMISSION

176. Theory. Telephone transmission cannot be treated wholly from the standpoint of analytical theory, but must be handled in part from an empirical standpoint. One telephone line can be compared with another when the high-frequency constants are known, on the basis of the mathematical theory of electrical energy transmission over a linear circuit possessing distributed resistance, reactance, capacitance and leakance. The only satisfactory method of comparing one telephone set with another, however, is by means of comparative tests and empirical standards of speech transmission.

177. Transmission equivalents are usually stated in terms of the lengths of No. 19 A.W.G. standard cable (88 ohms per mile, metallic; and 0.054 mf. per mile, mutual, at 800 cycles per sec.) which give the same total transmission losses as the lines or equipment in question.

178. Empirical standards of transmission are usually stated in terms of the transmission over a certain mileage of standard No. 19 A.W.G. cable, with certain types of telephones connected to each terminal and equipped in a certain specific manner. Such a definition serves to fix the standard volume of transmission, but not the quality. A standard equal to 30 miles of cable has been used for long-haul transmission, whereas standards equal to 20 miles or better have been considered in local service.

179. The range of frequencies which needs to be considered in telephone transmission is from about 80 to 3,000 cycles per sec. For many purposes the use of a **single equivalent frequency** of 750 or 800 cycles is sufficient.

180. The properties of conductors are treated as a whole in Sec. 4. In telephone transmission calculations the constants of the circuit should be those determined by actual test with sine-wave currents and e.m.fs. at 750 to 800 cycles per sec. The skin effect is important to consider; in small copper wires it is negligible, while in copper-clad steel wires it increases the effective resistance a few per cent. over the ohmic or real resistance, say 3 to 6 per cent., and in iron or steel wires it increases the effective resistance from 25 to 75 per cent. The skin effect also diminishes the effective inductance. The permeability of iron wire at high frequencies and low current-densities is about 70, and at power frequencies it is about 100 to 125. The energy loss in the dielectric of insulated conductors is also appreciable, as a rule, and shows itself as an increase in the effective leakage conductance.

181. The analytical theory of transmission is given in Sec. 2. It can be shown from the fundamental equations there given, and their solution, that the rate of attenuation on a very long uniform circuit is

$$\text{Propagation Constant} = \epsilon^{-\beta - j\alpha} \qquad (2)$$

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where ϵ is the base of Naperian logarithms, β is the attenuation constant and α is the wave-length constant. In a line of length l, the total attenuation is

$$\epsilon^{-\beta l - j\alpha l} = \epsilon^{-\beta l}(\cos \alpha l - j \sin \alpha l) \quad (3)$$

The quantity $\epsilon^{-\beta l}$ is the numerical magnitude of the attenuation and the quantity within the bracket is the directive or vector portion; the latter has always a numerical magnitude of unity, and is merely a unit vector expressed in terms of complex imaginary quantities. It follows that when two dissimilar lines give equal transmission,

$$\beta_1 l_1 = \beta_2 l_2 \quad (4)$$

182. The attenuation constant is given by the expression

$$\beta = \sqrt{\tfrac{1}{2}[\sqrt{(R^2+\omega^2L^2)(G^2+\omega^2C^2)} + (RG-\omega^2LC)]} \quad (5)$$

where R is the effective resistance in ohms per mile, L is the effective inductance in henries per mile, G is the effective leakage conductance in mhos per mile, C is the effective capacitance in farads per mile, and $\omega = 2\pi f$, where f is the frequency in cycles per sec.

183. The wave-length constant is given by a similar expression, which is

$$\alpha = \sqrt{\tfrac{1}{2}[\sqrt{(R^2+\omega^2L^2)(G^2+\omega^2C^2)} - (RG-\omega^2LC)]} \quad (6)$$

where the symbols have the same meaning as in the preceding paragraph.

184. The wave length is $\lambda = 2\pi/\alpha$, where λ is the length of one complete wave, α is the wave-length constant and $\pi = 3.1416$. If the line constants are taken per mile, as customary, λ will be in miles.

185. The velocity of propagation is $V = f\lambda$, where V = the velocity, λ is the wave length and f is the frequency. If λ is in mile units, V will be in miles per sec.

186. The KR law, which is strictly applicable only to cables, can be obtained by substituting $L = 0$ and $G = 0$ in Eq. 5. This will give $\beta = \sqrt{RC\omega/2}$. Therefore two dissimilar cables, neglecting the dielectric losses, will give equal transmission when

$$\frac{l_1}{l_2} = \sqrt{\frac{R_2C_2}{R_1C_1}} \quad (7)$$

where l_1 and l_2 are the respective lengths, R_1 and R_2 the respective resistances per mile and C_1 and C_2 the respective capacitances per mile. The term *KR* law comes from the use of the symbol K for capacitance; it might also be called the *CR* law.

187. The line impedance at the sending end is given by the formula

$$Z = \sqrt{\frac{R+j\omega L}{G+j\omega C}} \quad (8)$$

The **surge impedance** is equal to $\sqrt{R/G}$. For example the line impedance of 9 A.W.G. open copper metallic circuit at 800 cycles is about 690 ohms; for No. 9 copper clad, of 47 per cent. conductivity, it is about 830 ohms; and for a sample of No. 9 A.W.G. iron it was 1,640 ohms.

188. Wave reflection, or reflection loss, occurs at the junction of dissimilar impedances, such as the junction of open-wire line and cable, or more particularly at the junction of a loaded circuit with a non-loaded circuit.

189. Transmission tests are usually made under talking conditions by comparing one instrument with another, or one line circuit with another, and introducing extra cable in the more efficient circuit until the two are alike in talking volume as nearly as can be determined. The amount of extra cable measures the loss, which is expressed in so-called **cable equivalent**. For this work it is very convenient to have a portable artificial cable.

190. Artificial cable for transmission tests can be made in very compact portable form. A 32-mile artificial cable, equivalent to 32 miles of No. 19 A.W.G. metallic copper cable, 88 ohms loop resistance and 0.054 mf. (at 800 cycles per sec.) mutual electrostatic capacity, is a convenient size; the whole cable is subdivided into two 1-mile, one 2-mile, one 4-mile, one 8-mile and one 16-mile sections.

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191. Table of transmission equivalents of non-loaded metallic circuits in open wire

Type of circuit			Constants of circuit per mile of loop (2 wires)*			Transmission equivalent		
Gage No.	Bare or insulated	Physical pairs or phantoms	Effective resistance (ohms)	Effective inductance (henries)	Effective capacitance (mf.)	Miles equivalent to1 mile of No. 19 A.W.G. standard cable	Reciprocal	Miles equivalent to 30 miles of No. 19 A.W.G. standard cable
8 B.W.G.	Bare copper	Pairs	4.08	0.00337	0.00898	28.6	0.035	860
8 B.W.G.	Bare copper	Phantoms	2.04	.....	.....	34.5	0.029	1035
9 A.W.G.	Bare copper	Pairs	8.78	0.00359	0.00838	15.6	0.064	470
9 A.W.G.	Bare copper	Phantoms	4.39	.....	.....	18.5	0.054	555
12 S.W.G.	Bare copper	Pairs	10.26	0.00366	0.00822	12.7	0.079	380
12 S.W.G.	Bare copper	Phantoms	5.13	.....	.....	15.0	0.067	450
14 S.W.G.	Bare copper	Pairs	17.4	.....	.....	8.2	0.122	246
14 S.W.G.	Bare copper	Phantoms	8.70	.....	.....	9.5	0.105	285
9 A.W.G.	Bare copper clad (47%)	Pairs	18.9	0.00390	0.00838	8.1	0.123	243
10 A.W.G.	Bare copper clad (47%)	Pairs	23.5	0.00394	0.00820	6.8	0.147	204
12 A.W.G.	Bare copper clad (47%)	Pairs	37.2	0.00408	0.00786	4.9	0.204	147
14 A.W.G.	Bare copper clad (47%)	Pairs	59.4	0.00420	0.00755	3.6	0.28	108
8 B.W.G.	Bare iron (BB)	Pairs	.....	.....	.....	5.5	0.18	165
10 B.W.G.	Bare iron (BB)	Pairs	.....	.....	.....	4.0	0.25	120
12 B.W.G.	Bare iron (BB)	Pairs	85.0	0.0150	.....	3.1	0.32	93
14 B.W.G.	Bare iron (BB)	Pairs	.....	.....	.....	2.5	0.40	75
14 A.W.G.	Copper (rubber and braid)	Pairs	27.1	.....	.....	1.2	0.8	36
18 A.W.G.	Copper (rubber)	Pairs	68.3	.....	.....	0.9	1.1	27
17 A.W.G.	Copper-clad (drop)	Pairs	.....	.....	.....	0.6	1.7	18

* NOTE: Leakage assumed to be negligible.

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Type of circuit			Constants of circuit per mile of loop (2 wires)			Transmission equivalent		
Gage No. A.W.G.	Construction	Physical pairs or phantoms	Resistance (ohms)	Capacity (mf.)	Insulation (megohms)	Miles equivalent to 1 mile of No. 19 A.W.G. standard cable	Reciprocal	Miles equivalent to 30 miles of No. 19 A.W.G. standard cable
19	Dry-core paper cable	Pairs	88	0.060	500	1.00	1.00	30
22	Dry-core paper cable	Pairs	176	0.083	500	0.60	1.66	18
22	Dry-core paper cable	Phantoms	88	.....	.....	0.68	1.48	20
22	Dry-core paper cable	Pairs	176	0.070	500	0.65	1.53	20
22	Dry-core paper cable	Phantoms	88	.....	.....	0.74	1.36	22
19	Dry-core paper cable	Pairs	88	0.074	500	0.90	1.11	27
19	Dry-core paper cable	Phantoms	44	.....	.....	1.01	0.99	30
16	Dry-core paper cable	Pairs	44	0.074	500	1.28	0.78	38
16	Dry-core paper cable	Phantoms	22	.....	.....	1.43	0.70	43
14	Dry-core paper cable	Pairs	27	0.074	500	1.61	0.62	48
14	Dry-core paper cable	Phantoms	13	.....	.....	1.82	0.55	55
13	Dry-core paper cable	Pairs	22	0.074	500	1.82	0.55	55
13	Dry-core paper cable	Phantoms	11	.....	.....	2.04	0.49	61
10	Dry-core paper cable	Pairs	11	0.074	500	2.55	0.39	77
10	Dry-core paper cable	Phantoms	5.5	.....	.....	2.85	0.35	86
19	Submarine (impregnated paper)	Pairs	88	.....	500	0.53	1.9	16
3 No. 22	Submarine (rubber)	Pairs	59	.....	.....	0.63	1.6	19
16	Submarine (impregnated paper)	Pairs	44	.....	500	0.71	1.4	21
22	Swbd. cable (cotton and silk)	Pairs	176	.....	100	0.45	2.2	14
19	Swbd. cable (cotton and silk)	Pairs	88	.....	100	0.59	1.7	18
19	Swbd. cable (wool)	Pairs	88	.....	100	0.67	1.5	20
16	Swbd. cable (wool)	Pairs	44	.....	100	0.91	1.1	27

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193. Inductance loading or Pupin coils* are now used extensively to improve transmission, although in America the art of loading is still a virtual monopoly under the patents which are held by the Bell system. Loading coils are made in toroidal form and inserted in the line as shown in Fig. 54, at intervals of about 8 miles in open wire and from 1 to 2.5 miles in cable. Such coils are also applicable, when properly wound, to phantom circuits. The transmission gains cannot be secured with very short lines, say 4 or 5 miles of No. 19 A.W.G. cable, or roughly 75 miles of No. 12 N.B.S.G. open copper wire. For further details see the literature in the bibliography, Par. **263**.

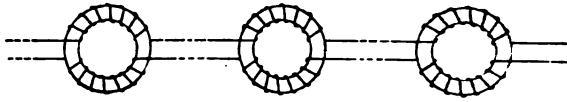


FIG. 54.—Method of connecting loading coils into a telephone line.

194. Experimental values of transmission equivalents for various types of telephone circuits have been determined by different investigators and are fairly well established. Tables of such values are given in Par. **191** and **192**.

195. Transmission equivalents of equipment and apparatus vary greatly according to the type and construction. The loss due to a bridged relay or drop, wound to 500 ohms, varies from 0.2 to 0.5 mile of standard No. 19 cable; if an efficient impedance coil be connected in series with the drop, the loss can be reduced to practically zero. A 1,000-ohm bridging bell has a loss of less than 0.1 mile. The loss due to series 2-mf. condensers is about 0.2 mile each. When an operator's set is bridged across a cord circuit the loss will vary from 0.5 to 4 or 5 miles.

The loss due to a repeating coil ranges from 0.5 to about 4 or 5 miles; efficient phantom coils have a loss as low as 0.05 to 0.15 mile each on the phantom leg and 0.25 to 2 miles on the side circuits. Telegraph composite sets have a loss of about 0.75 mile per set.

196. Reflection losses between non-loaded open wires of different sizes or side circuits and phantoms, or open wires and cables, are usually but a fraction of a mile of cable. In the case of a loaded open-wire circuit connected to an open-wire non-loaded circuit the reflection loss may become equal to 3 or 4 miles of standard cable.

197. Cost balance between open-wire line and cable. When a through line between two given points is comprised of a section of open wire connected to a section of cable, there is a certain size of open wire and a certain size of cable conductor which will provide the required standard of transmission (expressed as a certain fixed number of miles of standard cable) for the lowest annual cost, and any other combination of wire or conductor sizes, giving the same total transmission, will cost more.

198. Telephone repeaters of the audion or vacuum type are now in quite general use on the long lines of the Bell system, with excellent results. This type of repeater is by far the most successful yet developed. An extended description will be found in the paper on "Telephone Repeaters," by B. Gherardi and F. B. Jewett, *Trans.* A. I. E. E., Vol. XXXVIII, pp. 1286–1345. By means of this repeater the commercial range of telephone transmission has been extended to more than 3,000 miles and the use of long cable circuits has been greatly extended.

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* Pupin, M. I. "Propagation of Long Electrical Waves," *Trans.* A. I. E. E., 1899, Vol. XVI, p. 93; "Wave Transmission Over Non-uniform Cables and Long-distance Air-lines, 1900, Vol. XVII, p. 445.

Hayes, H. V. "Loaded Telephone Lines in Practice;" *Trans.* Int. Elec. Congress, St. Louis, 1904, Vol. III, Section G, p. 638.

Gherardi, B. "The Commercial Loading of Telephone Circuits in the Bell System;" *Trans.* A. I. E. E., Vol. XXX, 1911, pp. 1743 to 1773.

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TELEGRAPH TRANSMISSION

199. The theory of telegraph transmission has been developed from a number of standpoints. Herbert* has treated it empirically for English (open-circuit) practice, while Kennelly† has handled it from the purely analytical standpoint, regarding morse impulses as nearly the equivalent of a low uniform frequency (Par. **89**). The author has applied the leakage theory to uniform open-wire lines, for American practice, with results given in Par. **202**. None of these theories is perhaps satisfactory from the standpoint of every type or condition of line met in practice, but collectively they form a fairly reliable guide.

200. The leakage theory as applied to uniform aerial (low-capacitance) lines, derived from the theory of the distribution of continuous currents in the steady state, has been extensively studied by the author,‡ and appears to be applicable to open-wire lines of the closed-circuit type, if there are no considerable lengths of cable in circuit.

201. Commercial operative limits of transmission, with given line resistances and an assumed leakage conductance of 4 micromhos per mile, have been tabulated in Par. **202**, under the further assumptions next stated: single working, 150-ohm main-line relays, 300 ohms total resistance at each terminal, and a ratio of releasing to operating current equal to 0.75; differential polar duplex, 800-ohm polar relays, and a 300 ohm protective resistor at each terminal; differential quadruplex, 400-ohm polar relays, 800-ohm neutral relays, an e.m.f. of 90 volts on the short (polar) side, ratio of long to short voltages equal to 3.5 and a 600-ohm protective resistor at each terminal.

202. Table of commercial operative limits, with closed-circuit single, duplex and quadruplex Morse working

(Based on a leakage conductance of 4 micromhos per mile)

Resistance per mile (ohms)	Maximum permissible length of line§ (miles)		
	Duplex (two sides)	Simplex or single	Quadruplex (four sides)
2	783	597	531
3	658	510	442
4	580	450	386
6	485	376	313
8	425	331	268
10	384	299	236
15	318	248	186
20	278	217	156
25	250	195	135
30	229	179	120
40	200	156	98.7
50	180	140	84.3

203. The KR law of transmission as developed by Herbert (see footnote of Par. **199**) can be stated as follows:

$$W = \frac{A}{KR} \qquad (9)$$

where W is the maximum commercial speed in words per min., K is the total capacitance and R is the total resistance of the line; A is a constant having a value of 10,000,000 for open-wire lines of iron, 12,000,000 for open-

* Herbert, T. E. "Telegraphy;" Whittaker and Co., London, 1906, Chap. XVII.

† Kennelly, A. E. "The Application of Hyperbolic Functions to Electrical Engineering Problems;" The University of London Press, 1912.

‡ Fowle, F. F. "Telegraph Transmission;" *Trans.* A. I. E. E., Vol. XXX, 1911, pp. 1683 to 1741: A Study of Telegraphic Transmission, *Telephone Engineer*, Vol. IV, Oct., 1910, p. 171, continued to Vol. VI, July, 1911, p. 49.

§ No intermediate stations.

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wire lines of copper, and 18,000,000 for cables of the submarine type with gutta-percha insulation. The assumed working conditions are 8 milliamperes of line current, not less than 100 volts impressed e.m.f. from a source whose internal resistance does not exceed 3 ohms per volt, and a shunted condenser at the receiving end. For a speed of 400 words per min. Herbert gives the following limits of distance:

	Miles	Km.
150-lb. aerial copper line	590	950
100-lb. aerial copper line	490	785
450-lb. aerial iron line	360	580
400-lb. aerial iron line	290	465
Gutta-percha underground cable	83	134
Screened paper cable, 40-lb	128	210

204. Intermediate stations on the line (in single working) increase the total resistance of the line and decrease the transmission efficiency. If the stations are about uniformly spaced, every few miles, the effect can be equated by adding the resistances of the intermediate stations to the resistance of the line wire. It is good practice to employ 35-ohm main-line relays for way circuits, with a line current of at least 60 milliamperes.

205. Effect of varying leakage on single (simplex) working, with a line measuring 10 ohms per mile

(No intermediate stations)

Insulation resistance (megohm-miles)	Leakage conductance (micromhos per mile)	Operative limit (miles)
1.000	1.0	624
0.500	2.0	433
0.250	4.0	299
0.125	8.0	204

206. The use of automatic repeaters becomes necessary when the total distance between the line terminals exceeds the operative mileage limit of the line wire under the most adverse weather conditions (maximum leakage). In providing for through telegraph transmission over long distances it is uneconomical to employ line wires having more than the necessary tensile strength,* because one or more sets of repeaters can readily be installed in such a manner as to subdivide the line electrically into sections suitable for the electrical characteristics of the line wire. Repeaters are installed about once in every 450 to 500 miles with No. 9 A.W.G. copper wire, and at shorter intervals with wires of lower efficiency.

CONSTRUCTION

207. The types of outside construction are open wire, aerial cable, and underground cable. These types are briefly described in the following paragraphs. Also see "National Electrical Safety Code" for minimum strength requirements.

208. Pole lines comprise poles, cross-arms, guy stubs, braces, guys, anchors, and the right of way. The aerial wire or cable construction is not usually included under the definition of pole lines, but classed by itself.

209. Poles. The timber used most extensively is cedar, and next in order come chestnut, oak, pine, and cypress.† Poles as they come from the stump require peeling, roofing and gaining before they are ready for use; in addition the poles for certain classes of construction require shaving, stepping and painting. The sizes of poles used in line construction are regulated by the loads they will ultimately be required to carry. A number of the larger telephone companies classify their cedar poles as follows:

* Fowle, F. F. "Economical Spacing of Telegraph Repeaters;" *Telephone Engineer*, Vol. VI, Sept., 1911, p. 147.

† See reports of the U. S. Forest Service, Dept. of Agriculture.

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Length in ft.	Circumference (in.)									
	Class A		Class B		Class C		Class D	Class E	Class F	Class G
	Top	6 ft. from butt	Top	6 ft. from butt	Top	6 ft. from butt	Top	Top	Top	Top
20	.....	.....	.....	.....	.....	.....	.....	.....	15.5	12.5
22	.....	.....	.....	.....	.....	.....	.....	15.5	15.5	12.5
25	.....	.....	22	32	18.8	30	18.8	17.3	15.5	12.5
30	24	40	22	36	18.8	33	18.8	18.8	18.8	.....
35	24	43	22	38	18.8	36	18.8	18.8	18.8	.....
40	24	47	22	43	18.8	40	18.8	18.8	18.8	.....
50	24	53	22	50	18.8	46	22.0	22.0	18.8	.....

Class A poles are used in lines carrying 50 to 80 wires; Class B poles for 40-wire lines; Class C poles for 20-wire lines; Class E for 10-wire lines; Classes F and G for light farmer lines and bracket lines. Also see Sec. 4, on timber.

210. Pole setting. The depth of poles in the ground should be as follows, for ordinary soil or for solid rock.

Length of pole (ft.)	Depth in the ground		Length of pole (ft.)	Depth in the ground	
	Earth (ft.)	Rock (ft.)		Earth (ft.)	Rock (ft.)
20	4.0	3.0	50	7.0	4.5
25	5.0	3.0	55	7.5	5.0
30	5.5	3.5	60	8.0	5.0
35	6.0	4.0	65	8.5	6.0
40	6.0	4.0	70	9.0	6.0
45	6.5	4.5	75	9.5	6.0

Also see requirements of "Nat. Elec. Safety Code."

211. Reinforced concrete poles have been used to a limited extent, largely on an experimental basis. They are not in sufficient use to warrant any considerable description here; see Still, A. "Over-head Electric Power Transmission," New York, 1913. Coombs, R. D. and Slocum, C. L. "Reinforced Concrete Poles;" Universal Portland Cement Co., 1910.

212. Preservative treatment of poles to prevent decay, especially below the ground line, is constantly becoming more common. Among the preservatives employed are creosote, carbolineum avenarius, creolin, spirittine, coal

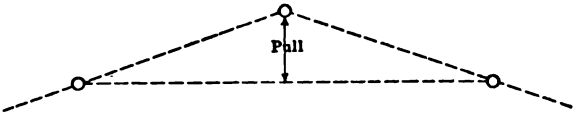


FIG. 55.—Measurement of "pull" on pole-line curve or turn.

tar, zinc chloride and others. There are three methods of treatment, closed-tank process (treating entire pole), open-tank process and brush treatment. The open-tank method, for treating the butts (only) with coal-tar creosote, is recommended as superior to the brush treatment. See publications of the Forest Service, U. S. Dept. of Agriculture, Washington, D. C.

213. Spans. On level straight sections the spans should be about as follows: 40-wire lines, 130 ft.; 20-wire lines, 130 to 150 ft.; 10-wire lines, 150

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to 200 ft. A span of 132 ft. corresponds to 40 poles per mile; the number of poles per mile is seldom less than 30 and in some cases, for heavy lines or in exposed locations, may be as high as 50 or 60 per mile. On curves or turns the spans are regulated by the "pull," which is defined in Fig. 55. The following table shows the lengths of span for different pulls.

Pull (ft.)	10-wire line (span in ft.)	20-wire line (span in ft.)	40-wire line (span in ft.)
1–5	150–175	130–150	130
6–10	140–160	120–140	120
11–15	130–145	115–130	110
16–20	120–135	110–120	100
21–25	115–125	105–115	90
26–30	110–120	100–110	75

214. Pole gains are usually 24 in. between centres, with the uppermost gain 12 in. from the pole top. The gains for the ultimate number of cross arms are usually cut before the pole is erected.

215. Approximate weights and dimensions of standard Washington fir cross-arms

Size 3½ in. by 4½ in., bored for 1½-in. pins, ¾-in. through bolt and two ¾-in. brace bolts; unpainted

Length ft.	Pins	Spacings			Weight (lb.)
		Between side pins (in.)	Between pole pins (in.)	End (in.)	
3	2	.....	28	4	10
4	4	12	16	4	13
5	4	17	18	4	17
6	4	21	22	4	20
6	6	12	16	4	20
8	6	17½	18	4	27
8	8	12	16	4	27
10	10	12	16	4	34

Lighter cross-arms, 2¾ in. by 3¼ in., are sometimes used.

216. Approximate weights and dimensions of yellow pine cross-arms. The dimensions of yellow pine cross-arms are the same as fir cross-arms given in Par. **215**, and the respective weights are approximately 6, 7, 10, 16, 21 and 25 lb. each. These arms are usually painted (red) to increase their life.

217. Cross-arms on adjacent poles face in opposite directions, except on steep hills or grades, when they face up-grade; on curves they should face toward the centre of the curve. In general they should be so faced that the stresses pull them against the pole. Double arms are often used at long spans and railroad crossings.

218. Pole and cross-arm construction is shown in **Fig. 56. Cross-arm braces** (24 in. or 26 in. long) should be attached as shown in the figure. For further details on construction see McMeen, S. G. and Miller, K. B. "Telephony;" Amer. School of Correspondence, Chicago, 1912; also Thiess, J. B. and Joy, G. A. "Toll Telephone Practice;" D. Van Nostrand Co., New York, 1912.

219. Pins are made of locust, hedge, oak, maple and elm; the preferable wood is locust. The standard size is 1½ in. by 9 in. For light cross-arms the pins are 1½ in. by 8 in.

220. Guying or reinforcement of a pole-line is necessary on curves and at corners or abrupt turns. This is usually done by means of steel guy strand attached near the top of the pole or at the load centre, and anchored to a buried log or plank, or some form of patent anchor. Methods of guying are

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shown in Figs. 57 and 58; in some cases it is desirable also to guy from the top of pole 1 to the butt of pole 2, and from the top of pole 4 to the butt of pole 3. Back-braces are required on cross-arms on corner poles.

221. Guy strand consists of a galvanised seven-wire strand (or concentric-lay cable) and is usually obtainable in four standard sizes having ultimate tensile strengths of 4,000 lb., 6,000 lb., 10,000 lb. and 16,000 lb., respectively.

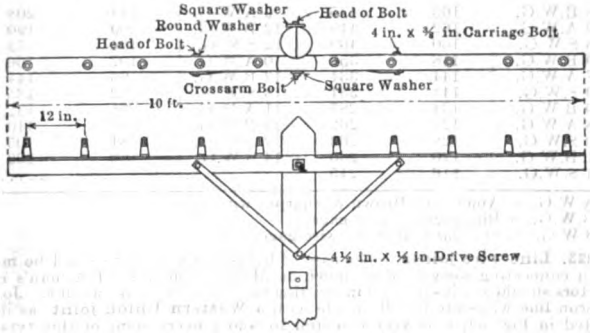
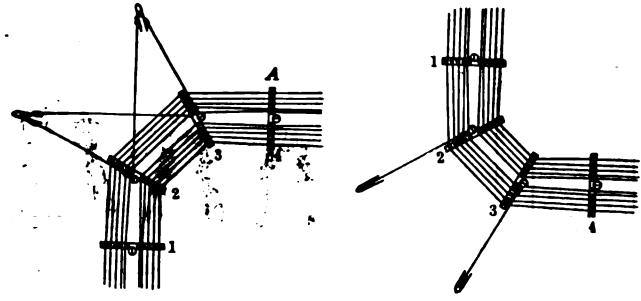


FIG. 56.—Standard pole top and cross arm.

222. Wire used in aerial construction ranges in size from No. 8 B.W.G. (435 lb. per mile) to No. 14 S.W.G. (102 lb. per mile) in hard-drawn copper and from No. 6 B.W.G. (573 lb. per mile) to No. 14 B.W.G. (96 lb. per mile) in galvanised annealed iron and steel. The independent telephone companies employ No. 6 to No. 12 A.W.G. copper, while the Bell companies have



FIGS. 57 and 58.—Methods of guying at a corner.

standardised No. 8 B.W.G. and No. 12 and No. 14 S.W.G. copper. For the properties of wire see Sec. 4.

Insulated open wire is usually covered with two cotton braids saturated with weather-proof compound; this is known as ordinary weather-proof wire. Twisted pairs are insulated with a covering of rubber compound and a braid over each conductor. For weights of insulated wire see Sec. 12 and Sec. 13.

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Gages, diameters and weights of hard-drawn copper telephone wires

(Also see wire tables in Sec. 4)

Number	Diam. (mils)	Lb. per mile	Number	Diam. (mils)	Lb. per mile
8 B.W.G.	165	435	9 A.W.G.	114	208
6 A.W.G.	162	419	12 B.W.G.	109	190
8 S.W.G.	160	409	12 S.W.G.	104	173
9 B.W.G.	148	350	10 A.W.G.	102	166
7 A.W.G.	144	331	13 B.W.G.	95	144
9 S.W.G.	144	331	13 S.W.G.	92	135
10 B.W.G.	134	287	11 A.W.G.	91	132
8 A.W.G.	128	262	14 B.W.G.	83	110
10 S.W.G.	128	262	12 A.W.G.	81	105
11 B.W.G.	120	230	14 S.W.G.	80	102
11 S.W.G.	116	215	.....	.....	.....

A.W.G. = American (Brown & Sharpe) wire gage.
B.W.G. = Birmingham wire gage.
S.W.G. = Standard (British) wire gage.

222. Line-wire joints in the case of hard-drawn copper should be made with connecting sleeves, also known as McIntire sleeves. Lineman's connectors should always be used in twisting the sleeves to make a joint. Joints in iron line wires are usually made with a **Western Union joint**, as illustrated in Fig. 59; it is very essential to solder every joint of this type in order to prevent premature corrosion and preserve satisfactory electrical connection. Also see Rashman, C. T. "Some Tests on Splices in Galvanized Iron Wire;" *Electrical World*, Nov. 17, 1910, p. 1187.

224. Tie wires should be of the same size and material as the line wire except that they should be annealed or soft.

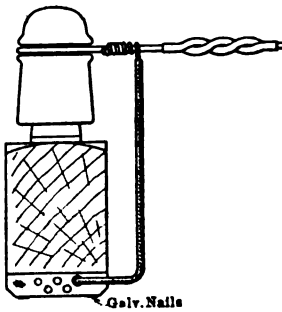


FIG. 60.



FIG. 59.—Western Union style of joint for iron wire.

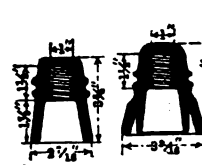


FIG. 61.

FIG. 62.



FIG. 63.

FIG. 60.—Method of attaching wire terminal to bridle cable.
FIG. 61.—Long-distance type glass insulator.
FIG. 62.—Western Union glass insulator.
FIG. 63.—Postal telegraph glass insulator.

225. Bridle cables are rubber insulated, and the individual conductors are carried from the main cable (up and down the pole) to their respective line wires by means of cleats beneath the cross-arms. Attachment to the line wires may be made by means of a soldered wrap on one leg of the dead-end turn around the insulator, or by means of a screw clamp on the line wire just outside of the dead-end. See Fig. 60.

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226. Test connectors are usually installed at intervals along a pole line, in order to provide facilities for opening the lines for test without cutting the wires. A pole thus equipped with test connectors is termed a **test pole.** The location of test poles is varied in different installations to suit convenience.

227. Line insulators are ordinarily made of glass, in one of the patterns shown in Figs. 61 to 63. Porcelain is used to a limited extent in place of glass, especially to secure the high insulation necessary on loaded circuits, but is more expensive. Porcelain is used to a much greater extent in Europe than in this country.

228. Sag table for hard-drawn bare copper line wire consisting of No., 12 S.W.G. (0.104 in. diam.) is as follows. The sags are given in inches.

Temp. (deg. fahr.)	Length of span (ft.)								
	75	100	115	130	150	175	200	250	300
−30	1.0	2.0	2.5	3.5	4.5	6.0	8.0	14.0	22.0
−10	1.5	2.5	3.0	4.0	5.0	7.0	9.0	16.0	26.0
+10	1.5	3.0	3.5	4.5	6.0	8.0	11.0	19.0	30.0
30	2.0	3.5	4.0	5.5	7.0	10.0	12.0	21.0	33.0
60	2.5	4.5	5.5	7.0	9.0	12.0	16.0	27.0	43.0
80	3.0	5.5	7.0	8.5	11.5	15.0	19.0	31.0	49.0
100	4.5	7.0	9.0	11.0	14.0	18.0	23.0	36.0	55.0

The sags for No. 14 S.W.G. (0.080 in. diam.) hard-drawn bare copper under like conditions, should be at least 2 in. greater than the above values for No. 12.

229. Transpositions are now usually made with an iron bracket or hanger mounted on the cross-arm in such manner that it supports the insulator which carries one of the wires below the arm, while the other wire is supported in the usual manner above the arm. Special insulators known as transposition insulators were formerly standard and are still used to some

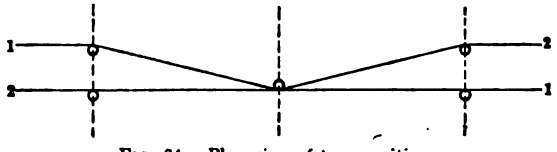


FIG. 64.—Plan view of transposition.

extent. These insulators are made sometimes in one piece with double grooves, and sometimes in two pieces, with one groove in each. In former practice the single-pin transposition was used very extensively, but is now superseded by the bracket type.

230. Phantom transpositions are made by means of upright iron brackets attached to the cross-arms; these brackets may support either transposition insulators or standard insulators, as designed.

231. Stresses in pole lines and wire spans are covered in Sec. 11 and Sec. 12.* In territories subject to sleet storms, the maximum stresses occur with combined sleet and wind loads. The maximum loads now usually assumed are those specified as "Heavy," "Medium," or "Light," in the "National Electrical Safety Code," promulgated by the Bureau of Standards. These three grades of loading apply respectively in three different zones into which the Bureau has subdivided the United States as a whole.

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* Also see Report of Committee on Overhead Line Construction; N. E. L. A., 1911 to 1921.

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232. Overhead wire clearances vary according to local conditions and the statute requirements. At **railroad crossings** the minimum clearance is usually prescribed by law, but this varies somewhat, being in the vicinity of 24 ft.; the local statute should always be looked up and followed.

233. High-tension crossings, or crossings between telephone and telegraph lines and high-tension (over 5,000 volts) high-energy lines should be specially constructed to minimise the hazard of accidental contact or electrical conduction between the two systems. The high-tension line is usually the stronger and should, for that reason, cross over the low-energy line. Where practicable, the crossing span of the high-tension line should be shortened until the free end of any broken phase wire in that span will swing clear of the wires or structure of the lower line. If the span cannot be shortened, the construction of the high-tension line should be amply strong. Cradles or baskets suspended beneath the high-tension wires are not recommended. For further details see the reference given in Par. **231** and in the Bibliography, Par. **263.**

234. Joint line construction with electrical distribution (central station) systems is now quite common in congested districts. Certain restrictions should be strictly observed in this class of construction; see National Electrical Safety Code. The proper arrangement is with the distribution lines on the upper cross-arms and the telephone wires below.

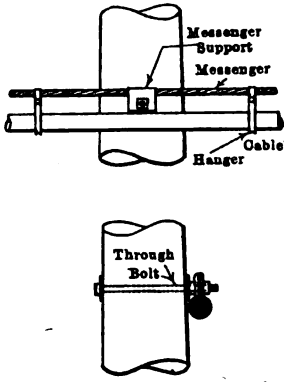


FIG. 65.—Aerial cable suspension.

235. Aerial cable construction is indicated in a general way in Fig. 65, which shows a single cable and messenger supported from a pole. Another cable can be supported on the opposite side of the pole in the same manner. When several cables are to be supported, an angle-iron cross-arm is attached to the pole and the messengers are suspended therefrom.

236. Messengers are usually made of seven-wire concentric-lay cable, each wire being of galvanised steel; such a cable is also known as a seven-strand cable. Messenger cables have been standardised to a considerable extent, employing three different sizes having ultimate tensile strengths of 6,000 lb., 10,000 lb. and 16,000 lb., respectively. For further details of galvanised strand see Sec. 4. For spans not exceeding 200 ft. the following rules are used to a considerable extent in determining the standard size of messenger to employ:

0–100 pr. No. 22, or 0–50 pr. No. 19 cable	6,000 lb.
100–200 pr. No. 22, or 50–100 pr. No. 19 cable,	10,000 lb.
Over 200 pr. No. 22, or over 100 pr. No. 19 cable,	16,000 lb.

237. Stresses in messenger spans are computed from the known or assumed loads as in the case of wire spans (Par. **231**; also see Sec. 11 and Sec. 12).

238. Table of Messenger Sags

(Bell Telephone Companies)

Span (ft.)	Sag (in).	Span (ft.)	Sag (in.)	Span (ft.)	Sag (in.)
80	16	110	26	150	44
90	20	120	30	175	62
100	22	130	34	200	82

For small cables, not larger approximately than 25-pair No. 19, the sag can be reduced about one-third.

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239. Cable rings (galvanized) attached to the messenger are now extensively employed for supporting the cable. Rings should be spaced from 15 to 20 in. apart.

240. Continuous cable lengths in aerial construction are limited by the amount of cable which can be pulled into place in one operation without injury. Except with very small cables, the continuous lengths do not ordinarily exceed 1,000 to 1,200 ft.

241. Cable splices. A straight splice is shown in Fig. 66. The conductors are twisted together in pig-tail fashion and folded back so that a

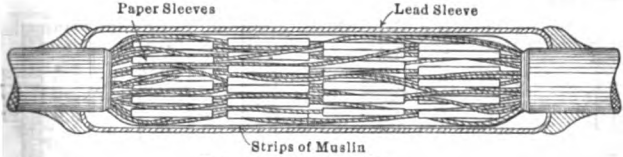


FIG. 66.—Cable splice.

paper tube or sleeve may be slipped over the joint to insulate it. These individual joints are staggered as shown in Fig. 66 and the whole is covered with a lead sleeve made water-tight by means of wiped joints. A number of forms of patented construction for such joints are also on the market.

242. Twisted pairs in rings, the latter supported from a messenger (perhaps carrying a cable also), constitute a form of construction now extensively used in reaching drops from a cable terminal or box.

243. The messenger should be bonded to the cable and grounded as a means of protection against foreign currents and lightning.

244. Grounds may be made by means of a coil of messenger or guy strand buried in coke, at a depth of 5 to 6 ft. in the ground, or by means of an iron pipe (about 6 to 8 ft. long and 1.5 in. diam.) driven into the ground. The first method is preferable. See Par. 158.

245. Underground conduit construction consists of a system of ducts laid from 2 to 4 ft. below ground, with intercepting manholes at intervals of 300 to 700 ft. (Fig. 68).

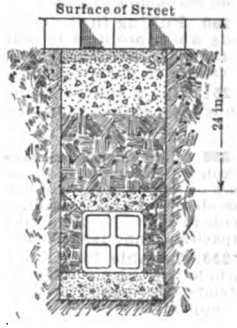


FIG. 67.—Section of four-duct underground conduit, showing cover.

246. Ducts are made of vitrified clay tile, creosoted wood, concrete, impregnated fibre, or iron pipe. The material most used is vitrified tile; this is made in both single duct and multiple duct, the latter including two-duct, three-duct, four-duct, six-duct, and nine-duct combinations in one piece. The length of a single piece of duct is from 1.5 ft. to 3 ft., and the duct opening about 2½, 3½ or 3½ in. in diameter.

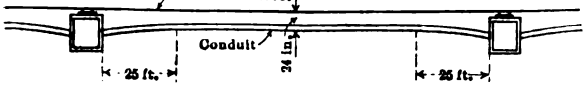


FIG. 68.—Section of underground conduit showing method of grading for drainage of ducts.

247. Standard conduit construction consists of some one of the above mentioned materials laid in a properly graded trench on a bed of Portland cement concrete and covered with an envelope on the top and sides, of the

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same material. (See Figs. 67 and 68.) There are many modifications of this type of construction.

248. Manholes (Fig. 69) may be constructed of sewer brick, rejected paving brick (vitrified), or reinforced concrete. There is not very much difference in the cost of manholes constructed by these three methods. The top of the manhole should have sufficient strength to support any traffic passing overhead. The cast-iron cover and supporting framework should be set in concrete to prevent corrosion. The sewer connection, if one is provided, should have a trap to prevent the rise of sewer gas. Ventilation, by perforations in the cover, is desirable to release foul or explosive gases.

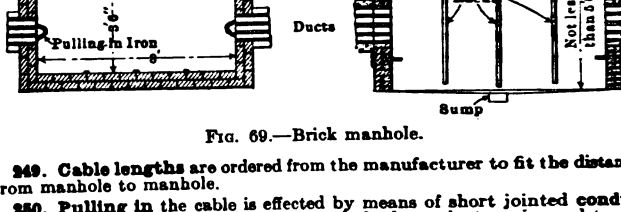


FIG. 69.—Brick manhole.

249. Cable lengths are ordered from the manufacturer to fit the distances from manhole to manhole.

250. Pulling in the cable is effected by means of short jointed conduit rods which are used to pull in rope and the latter in turn is used to pull in the cable with a hand or power capstan, or winch. About 600 to 700 ft of cable is as much as can be drawn in safely or conveniently in one length.

251. Cable splices are made in each manhole and the cables are trained along the sides of the manholes on the racks provided for the purpose.

TESTING

252. Two general classes of testing are necessary in telephone and telegraph practice; the first comprises those tests made to determine whether lines or equipment are in normal operative condition and, if not, to ascertain the character and location of the trouble; the second comprises those tests made to determine the properties of circuits, including resistance, inductance, capacitance and insulation.

253. Trouble location in ordinary maintenance work can be said to include tests for the following conditions: (a) electrical continuity; (b) open circuits; (c) crossed circuits; (d) grounded circuits; (e) noise or induction; (f) apparatus adjustment.

254. Continuity tests can be made with direct or alternating (ringing) current. Where available, an ordinary morse relay, sounder, key and necessary battery are extremely useful; this method of testing continuity is almost universal in telegraph practice. In telephone work great use is made of a magneto test, next described.

255. The magneto test set, used very extensively in continuity tests, is a very simple apparatus consisting merely of a hand-driven magneto generator and a buzzer or polarized bell, connected in series with each other and with the free terminals brought out to a pair of binding posts. See Par. 26 and 27.

256. The location of an "open" is not usually difficult in the case of cable conductors, and the capacity test is a common method. A number of patented devices are also on the market for finding the location of a break in a cable conductor. In the case of aerial open wire it is not always easy to find the location by means of a test; experienced wire chiefs are able to use the listening test to good advantage, judging the location by the noise on the circuit.

257. The location of a cross is usually a rather simple operation if a Wheatstone bridge (Sec. 3) is at hand, with which to measure resistances. A magneto or a morse set can be used to determine, first, which conductors are crossed. The Varley and Murray loop tests can also be used to locate crosses

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258. The location of a ground usually requires the use of the Varley loop test or the Murray loop test, next described.

259. The Varley loop test, Fig. 70, is frequently employed. When the bridge is balanced,

$$R_x = \frac{R_1R_2 - R_3R}{R_1 + R_3} \quad \text{(ohms)} \quad (10)$$

$$R_c = R_x + R_y + R_z \quad \text{(ohms)} \quad (11)$$

Equation (10) expresses the resistance of the grounded conductor from the bridge to the fault and (11) expresses the loop resistance of both conductors. Assuming the conductors to be uniform, it is a simple matter to calculate the distance to the fault. If desired, the resistance R can be connected in series with the other conductor, and in that case the formula given above (Eq.

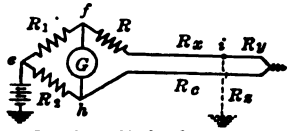


FIG. 70.—Varley loop test.

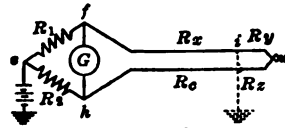


FIG. 71.—Murray loop test.

10) no longer holds true, and instead becomes, $R_x = R_1(R + R_c)/(R_1 + R_3)$. This test is especially useful because it is not affected by the resistance of the fault.

260. The Murray loop test, Fig. 71, is quite similar to the Varley test. The resistance of the defective conductor from the bridge to the fault is given by this formula, assuming the bridge to be balanced.

$$R_x = \frac{R_1R_c}{R_1 + R_3} \quad \text{(ohms)} \quad (12)$$

261. Insulation resistance comes under the class of high-resistance measurements (Sec. 3). A simple method in extensive use for measuring insulation resistance is the so-called **voltmeter method,** Fig. 72. The insulation resistance in megohm-miles is

$$R = lr_v\left(\frac{E}{V} - 1\right)10^{-6} \quad (13)$$

where E = potential in volts of the battery; V = voltmeter reading when connected to line: r_v = voltmeter resistance in ohms; l = length of line in miles. See discussion of this method, and a modification of it, by the author in the *Electrical World*, Feb. 6, 1904 and Mar. 9, 1912. The reciprocal of insulation resistance is termed leakance, and is a conductance expressible in mhos or micromhos.

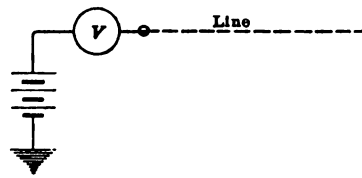


FIG. 72.—Voltmeter test for insulation resistance.

262. Quantitative measurements of telephone or telegraph circuits to determine resistance, inductance, reactance, capacitance and leakance, either to continuous or alternating currents, are covered as a whole in Sec. 3.

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RADIOTELEGRAPHY

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HIGH-FREQUENCY OSCILLATIONS

264. High-frequency circuits. All high-frequency circuits consist of inductance and capacity. Fig. 73 shows a closed circuit consisting of a spark gap, inductance and condenser. Fig. 74 shows a **Hertzian oscillator** in which the capacity is concentrated in the two spheres and the inductance is distributed throughout the straight wires. The power in watts taken up by such oscillatory systems is equal to

$$W = \tfrac{1}{2}\,\frac{CV^2N}{10^8} \qquad (14)$$

where C is the capacity in microfarads, V the maximum voltage in volts to which the condenser is charged, and N the number of times the spark passes per sec. At each spark the charge in the condenser oscillates back and

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forth until the energy is consumed either in the form of heat in the circuit itself, or through radiation of electrical waves. The number of times the charge surges back and forth before it is dissipated and the discharge across the spark gap ceases depends on the equivalent resistance of the various sources of energy loss in the circuit.

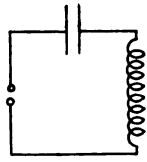


FIG. 73.—Closed oscillatory circuit.

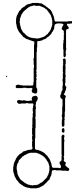


FIG. 74.—Hertzian oscillator.

265. Damped oscillations. Gradually decreasing oscillations of this kind are called damped oscillations and obey the law that each succeeding amplitude is a given fraction of the one before it. The constant difference between the natural logarithms of the successive amplitudes is known as the **logarithmic decrement.**

266. Spark. In the simplest form of sending set, the spark is placed directly in the antenna (see Figs. 74 and 78), but in order to use any except the smallest power (since the antenna capacity is in all ordinary cases small), a high voltage must be applied to the antenna. This necessitates the use of a long spark, which in turn introduces a high resistance into the antenna circuit, thus limiting the antenna current obtainable.

267. Coupled circuits. In order to get rid of this objectionable spark resistance, it is customary to excite the antenna circuit by means of a step-up transformer either inductively connected (Fig. 75) or directly connected (Fig. 76), the antenna circuit and the closed circuit containing the spark-gap

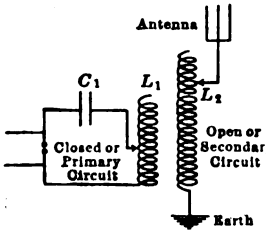


FIG. 75.—Inductive coupling.

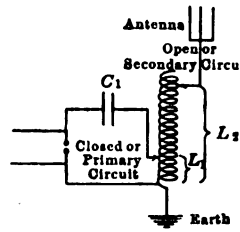


FIG. 76.—Direct coupling.

being tuned to resonance. Two circuits are in resonance, or the electric charges oscillate with the same frequency, when the product of the inductance and capacity in one circuit is equal to the product of the inductance and capacity in the other. A certain portion of the energy oscillating in the antenna is returned and is lost in the spark circuit; that is, the presence of the spark circuit is equivalent to a definite resistance introduced in the antenna. The amount of this equivalent resistance can be regulated by varying the mutual inductance between the antenna and spark circuit.

The fact that the spark length and the capacity in the spark circuit can be varied, provided the conditions of resonance are maintained, makes the double-circuit sending system far more flexible and capable of producing much higher currents in the antenna than the simple system shown in Fig. 78. The only disadvantage of the double-circuit system is that in general

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the two circuits must be adjusted separately, thus adding to the complication of making rapid changes in wave length.

THE ANTENNA

268. The antenna in radiotelegraphy may be considered to be a special case of the Hertzian oscillator (Fig. 74) in which the lower half is replaced by a conducting plane, the earth, to which it is connected (Fig. 77). Such an oscillator, if the earth be a perfect conductor, will have the same electric field distribution as a complete oscillator in free space, the lower half being indicated in the figure by the dotted lines.

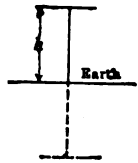


FIG. 77.—Antenna and image (earthed oscillator).



FIG. 78.—Simple antenna (Marconi).

269. The intensity of the electric field due to the radiation of such an oscillator (Par. **268**) in its equatorial plane and at a distance of several wave lengths from the oscillator may be expressed by the equation.*

$$E = 2\pi \left(\frac{lI_s}{\lambda d}\right) 3\times 10^{10} \qquad \text{(abvolts)} \qquad (15)$$

where l equals the length of the oscillator, I_s the current in the wire connecting the oscillator capacity spheres, and d the distance from the oscillator to the point in question. In transforming this equation to apply to the earthed antenna, the length of the equivalent oscillator must be taken as twice the height of the antenna. Bearing this in mind and changing to practical units,

$$E = 377\,\frac{hI_s}{\lambda d} \qquad \text{(volts per meter)} \qquad (16)$$

where I_s is in amperes and h, λ and d are in meters.

270. Antenna types. In practice the capacity sphere of the Hertzian

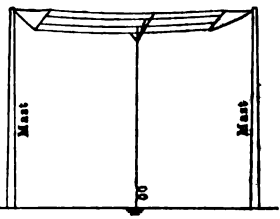


FIG. 79.—Flat-top antenna.

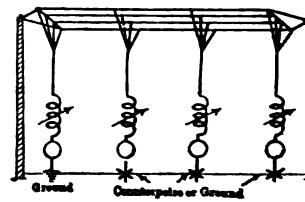


FIG. 80.—Alexanderson antenna.

oscillator is replaced by the various systems of wires of the antennas shown in Figs. 78, 79 and 80. Fig. 78 shows the original single wire antenna of Marconi. Fig. 79 is the flat-top or ship's antenna consisting of a number of

* J. Zenneck. "Lehrbuch d. drahtl. Telegr.," 1913, p. 46.

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parallel wires separated by spreaders and supported by two masts. Fig. 80 is an Alexanderson multiple tuned transmitting antenna. This consists of a long flat-top antenna with a number of tuned-down leads to one of which the generator is coupled. This gives a very low ground resistance. The leads are so tuned that their respective currents are in phase and the sum of these currents is the effective current of the antenna system. Another type is the platform antenna which is the one used in the high-power stations of the United States Navy. In this, the antenna is supported by three or more towers and may consist of a system of wires supported on spreaders or simply a network of wires between towers. All of these forms of antenna in practical use are subject to various modifications which cannot be entered into here. The effective height of the antenna is measured to the geometric centre of capacity of the wire system, if the ground is perfect (salt water) and there are no elevated masses of metal (steel supporting towers) close to the antenna. In land stations the actual effective height is from 50 to 90 per cent. of the measured height. That the height may be made as great as possible, it is desirable to increase the capacity of the upper portion, and to diminish the capacity of the leading-down wires, keeping them bunched together and using only enough to supply proper conductivity.

271. The amount of power which can be introduced into an antenna (Eq. 14) is proportional to its capacity, the square of its maximum voltage, and the number of times it is charged per sec.; *i.e.*, the spark frequency. The voltage is limited by the insulation and on shipboard should not exceed 70,000 volts maximum. The fact that the power for a given voltage is proportional to the spark frequency shows the great advantage of making the latter large, and explains why 60-cycle apparatus will not deliver a large amount of power.

272. Antenna capacity required per kilowatt of antenna power

Maximum antenna potential	1,000 sparks per sec.	120 sparks per sec.
50,000 (volts)	0.0008 (mf. per kw.)	0.0067 (mf. per kw.)
71,000	0.0004	0.0033
100,000	0.0002	0.0017

273. Power in antenna of 0.001 microfarad capacity at 50,000 volts maximum potential*

Sparks per second	Kilowatts	Antenna current†
120	0.15	5.0 amp.
240	0.30	7.1 amp.
500	0.625	10.2 amp.
1,000	1.25	14.3 amp.

274. Capacity required per kw. at 1,000 sparks per sec. and various voltages

Volts, (max.)	Mf. per kw.	Volts, (max.)	Mf. per kw.
14,500	0.010	25,000	0.003
17,700	0.006	31,400	0.002
22,400	0.004		

275. Calculation of antenna capacity. The capacity excluding leads of all antennas having their wires not too widely spaced can be very approximately represented by the formula

$$C = (4\sqrt{a} + 0.88a/h)(1 + 0.015l/b) \times 10^{-3} \qquad (17)$$

where c is the capacity, a the area, h the mean height, l the length and b the breadth in microfarads and meters. The elongation factor $(1 + 0.015l/b)$ may be neglected when the length l is less than eight times the breadth b.

* *Journal* of the Washington Academy; 1911, Vol. I, p. 5.

† Antenna resistance assumed to be 6 ohms.

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With parallel-wire antennas of medium dimensions, a spacing of one meter will generally insure over 90 per cent. of the possible capacity.

276. Radiation resistance. The process of radiation withdraws energy from the antenna and it is customary to speak of radiation resistance, meaning the equivalent resistance which would consume the same energy as that withdrawn from the antenna by radiation. If the height from the earth to the centre of capacity of the antenna system is h, and if λ is the wave length, the radiation resistance* is approximately

$$R = 1{,}600\,\frac{h^2}{\lambda^2} \qquad \text{(ohms)} \qquad (18$$

277. Table of antenna radiation resistances (ohms)

(h = height to center of capacity of conducting system)

Wave length (meters)	h = 40 ft.	h = 60 ft.	h = 80 ft.	h = 100 ft.	h = 120 ft.	h = 160 ft.
200	6.0	13.4	24.0	.....	.....	.....
400	1.5	3.4	6.0	9.3	13.4	.....
600	0.66	1.5	2.7	4.1	6.0	10.6
1000	0.24	0.54	0.95	1.5	2.1	3.8
2000	.....	0.134	0.24	0.37	0.54	0.95
3000	.....	.....	0.106	0.17	0.24	0.42
4000	.....	.....	0.060	0.093	0.134	0.24

Wave length (meters)	h = 200 ft.	h = 250 ft.	h = 300 ft.	h = 450 ft.	h = 600 ft.	h = 1,200 ft.
600	16.4	.....	13.5	.....	.....	.....
1000	6.0	9.3	3.4	.....	.....	.....
2000	1.5	2.3	1.5	7.5	13.4	.....
3000	0.66	1.03	0.84	3.4	6.0	24.0
4000	0.37	0.58	0.47	1.9	3.4	13.4
6000	0.16	0.26	0.37	0.84	1.49	6.0

The above table is calculated on the assumption that the antenna represents a Hertzian oscillator (Fig. 77). On account of the shapes of the antennas actually used, and the fact that the earth in most cases is not an ideal conductor, the radiation resistances actually observed are in general from 25 to 90 per cent. of the values given in the table.

278. Antenna ground connections. The outward and inward movement of the lines of electric force during the oscillations in the antenna give rise to earth currents. These earth currents are most intense in the immediate neighborhood of the antenna, and if the earth is a poor conductor a large waste of energy ensues. To guard against this loss, a radiating network of wire is placed beneath and around the antenna. In the case of a flat-top antenna, the radius of this wire net should not be less than the length of the horizontal portion of the antenna. In addition, if ground water is easily reached, copper plates connected to the wire net are buried so as to reach the water. Actual contact with the water is of less importance however than the proper arrangement of the wire net. On shipboard, the good conductivity of salt water and the conducting hull of the ship ensure a good ground if proper connection to the hull is made.

279. Directive antennas. There are many types of antennas which have directive characteristics, among the most important being the long low antenna, the loop antenna and the ground antenna.

280. The loop antenna. This type of antenna is widely used for direction finding and in connection with stray reducing circuits. It is made up of one or more turns of wire generally wound on a form rectangular in shape. The number of turns which are used for any given wave length is determined

* Ruedenberg, R. Ann. d. Phys.; Vol. XXV, p. 460; 1908.

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by the length and height of the loop, the type of detector used and the spacing of the turns. The loop is generally wound so that its length and height are several times its width. The vertical wires of an ordinary multi-loop may be considered as antennas having heights equal to the vertical height of the loop wires. If it were possible to completely shield one end of the loop, then the other end would be in effect equivalent to an antenna having a height equal to the vertical height of the loop times the number of turns in the loop, but since it is impossible to completely shield one end of the loop, the combined effect of the loop with respect to any point P will be that of two antennas having heights equal to the vertical height of the loop times the number of turns in the loop, and having currents out of phase by the amount $\frac{2\pi l \cos \alpha}{\lambda}$ where l is the length of the loop, α the angle between the plane of the loop and the point P, and λ the wave length corresponding to the frequency of the current in the loop. The solid line, Fig. 81, shows graphically the directive characteristic of a loop antenna. No current flows in the loop when its plane is at right angles to the direction of the transmitting station, the currents induced in the vertical wire at one end of the loop being equal and opposite to those at the other end. The ordinary antenna is practically non-directional and has a characteristic such as is shown by the dotted line in Fig. 81. If the effects of both antenna and loop are combined on the receiver, the resulting characteristic is that shown by the dash line in Fig. 81. When the effect of the antenna on the receiver is properly adjusted, the combination of loop and antenna will be sensitive to signals from one direction in the plane of the loop and will be practically shielded in the opposite direction. This effect may be shifted 180 deg. by reversing either the loop or antenna and ground leads. This shielding effect of a loop antenna combination is made use of in eliminating the directional type of static when such static comes from a direction other than the direction of the transmitting station.

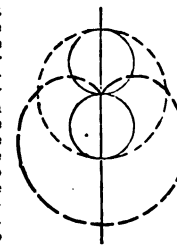


FIG. 81.

281. The flat top antenna may be thought of as a combination of loop and antenna, the loop being a single turn made up of the antenna lead, the antenna, a vertical return by displacement currents at about half the horizontal length of the antenna, and the ground. In order that such a flat top antenna be directive, it must be of such dimensions for a given wave length that it will have a loop effect which is comparable with the antenna effect. This condition is realized only in an antenna having a length much greater than its height.

282. Wave length. If no inductance coil is introduced into the antenna, it oscillates with a period corresponding to the distributed inductance and capacity of the antenna wires, and the wave length produced is called the fundamental wave length of the antenna. If it is desired to increase this wave length, inductance coils are placed in series between the antenna and the earth, and if it is desired to decrease it, a condenser is placed between the antenna and the earth. In the case of the excitation of the antenna by the closed circuit, it is of course necessary to have a certain amount of inductance in the antenna for the purpose of coupling.

METHODS OF EXCITING THE ANTENNA

283. The antenna, in the case of damped wave transmission, is usually excited by a closed circuit composed of a spark gap, inductance, and capacity to which it is coupled either inductively or directly (Figs. 75 and 76). If the mutual inductance between the two circuits is large, they are said to be closely coupled; if small, they are loosely coupled. The coupling is defined as $K = M/\sqrt{L_1 L_2}$. In the case of close coupling, owing to the mutual reactions between the circuits, oscillations of two wave lengths are produced in each circuit, even though the two circuits singly are tuned to resonance with each other. As the coupling is loosened, the two wave lengths approach each other and eventually merge. It was formerly customary to

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employ close coupling, but modern practice finds that the greatest range is attained with a coupling loose enough to cause the antenna to radiate wave of a single frequency except when quenched gaps are used.

284. Types of spark gap. Practically all spark sets make use of some form of quenched gap, rotary gap, or impulse gap. For small sets or for emergency use the fixed gap, such as that found on a spark coil, is sometimes used.

285. The rotary gap (Fig. 82) usually consists of two stationary electrodes with a rotating disc provided with projecting metal spokes or knobs which form the movable electrodes. The disc is usually attached to the shaft of the alternator and insulated from it, and is so adjusted that the maximum potential in the circuit is reached just before the movable electrodes come opposite the stationary electrodes. This ensures the regular passage of the spark, and the rapid motion produces sufficient cooling to prevent the formation of an arc. When used with a 500-cycle alternator, a pure musical note of 1,000 vibrations per sec. is produced in the receiving telephones. This high-pitched musical note is particularly advantageous in telephonic reception, being easily read through the atmospheric disturbances.

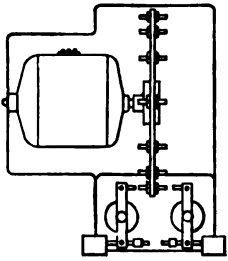


FIG. 82.—Rotary spark gap.

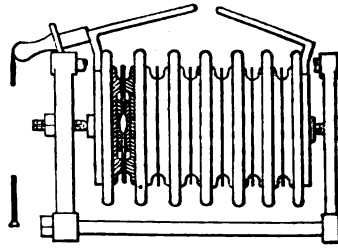


FIG. 83.—Quenched spark gap.

286. The quenched gap (Fig. 83) consists of a number of plates insulated from each other and separated by spaces of a fraction of a millimeter. It is in reality a number of gaps in series. On account of the spark being divided up into many parts in close proximity to large surfaces of metal, the cooling is very rapid. This, in addition to the rapid flow of energy from the closed circuit into the antenna, causes the spark to go out after four or five complete oscillations, and before a sufficient time has elapsed for any of the energy transferred to the antenna to return to the closed circuit. By adjusting the mutual inductance between the two circuits it is possible to make this quenching take place at the exact moment when practically all the energy is in the antenna. The fact that no energy can flow back into the closed circuit does away with the complicated reactions of ordinary double-circuit sending, and ensures that the radiated oscillations shall be of only one wave length. This gap is slightly more efficient in transferring energy to the antenna than the rotary gap.

UNDAMPED OSCILLATIONS

287. Advantages of undamped oscillations. Oscillations produced from the electric spark form damped wave trains with intervals between in which no energy is given off. If, instead of supplying energy merely at the beginning of the wave train, a constant source of supply can be obtained, the oscillations will continue indefinitely and with equal amplitude. The use of such undamped oscillations in radio communication has a number of advantages: first, if the energy is divided among a great number of waves of equal amplitude, instead of being concentrated in a few wave trains, the maximum voltages required for a given amount of power are very much less than in the case of damped waves, and consequently the insulation of the apparatus is much less difficult, and much larger amounts of energy can be sent out from mode-

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rate sized antennas. Second, undamped oscillations allow a greater sharpness of tuning and enable a looseness of coupling to be used at the receiving station between the antenna and secondary which greatly reduces the danger of interference and disturbance from atmospheric discharges.

285. Production of undamped oscillations. High-power undamped wave transmitting stations usually employ either the arc generator or some form of high frequency machine such as those designed by Alexanderson,* Goldschmidt,† Arco,† and others. Arc generators of 1000 kw. and high frequency machines of 500 kw. have been built. Vacuum-tube undamped transmitting sets of 50-kw. capacity are now in use and sets of much larger capacity are being developed.

289. The arc method of producing oscillations was discovered by Elihu Thomson in 1892 and has been developed by V. Poulsen, R. A. Fessenden and others. In this method a circuit containing suitable inductance and capacity is placed around the arc as shown in Fig. 88. Choke coils and resistance are placed in the main dynamo circuit to control the voltage and to prevent the oscillations from running back into the dynamo. When the shunt condenser circuit is closed around the arc a part of the current flows into the condenser thus robbing the arc of a portion of its current. But since the arc has the characteristic that the potential across the arc increases as the current decreases, this decrease in current increases the potential difference and the condenser continues to charge. At the next instant, however, the condenser commences to discharge, increasing the direct arc current until it is entirely discharged. Then the process repeats itself. For the best results it is necessary that the direct-current voltage be 500 volts or more, and that the positive electrode be capable of conducting heat rapidly away.

290. Poulsen arc. In the Poulsen arc, the positive electrode is copper and the negative carbon, and the arc is formed in a chamber filled with hydrogen or a hydrocarbon gas or vapor. Hydrogen being an excellent conductor of heat assists materially in the rapid cooling. A common method of producing a hydrocarbon vapor is to allow alcohol to fall drop by drop into the heated arc chamber. To still further increase the energy of the oscillations in the Poulsen apparatus the arc is formed in a strong magnetic field at right angles to its length. This is the type of arc which is used at high-power arc transmitting stations.

291. The arc circuit. When the arc is used for producing oscillations in a radiotelegraphic antenna, it is customary, when the antenna is of sufficient capacity, to place the arc directly in it (Fig. 85), thus doing away with the necessity of

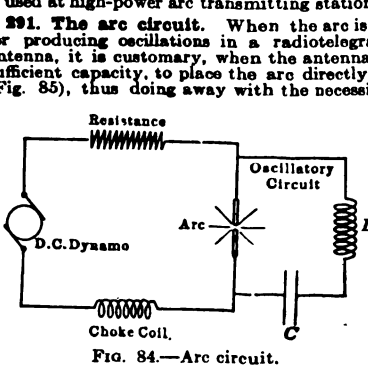


FIG. 84.—Arc circuit.

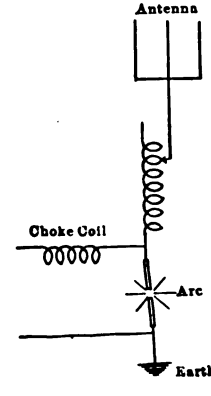


FIG. 85.—Arc in antenna.

ining two separate circuits, the inductance and capacity of the antenna aking the place of the closed-circuit inductance and capacity of Fig. 84.

* Alexanderson, *Proc.* I. R. E., Vol. VII, pp. 363–390.
† Zenneck Wireless Telegraphy.

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THE WIRELESS TELEPHONE

292. General principles. As long as continuous oscillations are of the same intensity, they produce no sound in the telephones attached to an ordinary radio receiver. If, however, a microphone transmitter be placed in the sending circuit, any words spoken into the transmitter are faithfully reproduced in the telephones of the receiver.

293. The range of telephonic transmission is becoming more and more extended with the development of high-power vacuum tubes. Satisfactory speech transmission over distances of 500 miles is not uncommon, while under the most favorable conditions distances of 3,000 miles have been covered.

294. Applications. The radio telephone has been developed to a state where it is very useful in military operations, especially in connection with the air service. Telephone communication is possible between planes in flight and between planes and ordinary radio stations. Conversations have been carried on between the pilots of two machines in flight when the distance between the planes was more than fifty miles. The radio telephone is also used for entertainment purposes.

TRANSMISSION OF WAVES FROM THE SENDING TO THE RECEIVING ANTENNAS

295. Day transmission.—The radiation from a radiotelegraphic antenna may be conceived to consist of lines of electrostatic force with their ends terminating in positive and negative electric charges at the earth's surface somewhat as shown in Fig. 86. At moderate distances the strength of the electric field is represented by Eq. 16. For distances of more than 100 miles, over sea water, and for still shorter distances over land, an absorption of energy appears which modifies the results of Eq. 16. This absorption is due in part, at least, to the resistance of the earth to the passage of the positive and negative electric charges at the base of the electrical wave. At great distances the bottom of the wave is so much retarded that the wave front becomes bent forward. When brought into this position the electric field can be divided into two components, one at right angles to the earth's surface and the other parallel to it. The latter produces oscillatory earth currents which, while they withdraw energy rapidly from the wave, make possible the reception of signals by means of long horizontal antennas, on or in the ground. Experiments by the U. S. Navy Department extending up to a distance of 2,000 miles have given results for flat-top antennas which may be represented by the following empirical formula*

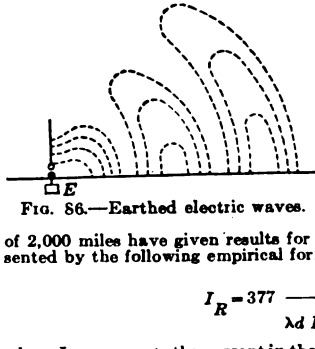


FIG. 86.—Earthed electric waves.

$$I_R = 377 \frac{h_1 h_2 I_s}{\lambda d R \sqrt{1+\frac{\delta_1}{\delta_2}}} e^{-\frac{0.0015 d}{\sqrt{\lambda}}} \quad \text{(amp.)} \quad (19$$

where I_R represents the current in the receiving antenna, I_s the current in the sending antenna, R the receiving resistance, d the distance, λ the wave length, and $h_1 h_2$ the height to the centre of capacity of the sending and receiving antennas, respectively, the currents being given in amp. and all lengths in km. The formula applies to day signals with transmission entirely over salt water. A similar formula will probably apply to land transmission except that the absorption coefficient (0.0015) is much larger and depends on the character of the ground over which the waves pass and also on the season of the year. It is found for example, that the absorption between New York and Washington at a wave length of 1,000 meters, is approximately three times as great in summer as in winter. The formula

* Austin L. W. Bulletin Bureau of Standards, Vol. VII, p. 362 (reprint 159), 1911, and Vol XI, p. 69 (Reprint 226), 1914.

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indicates that for short distances stronger signals may be obtained by the use of short wave lengths, while for great distances longer wave lengths, from 3,000 to 25,000 meters, are used. Over land for distances greater than 150 miles, wave lengths of more than 2,000 meters are generally desirable.

296. Calculated relation between antenna current and distance for two ships with antenna heights of 130 ft., using damped waves and crystal detectors

$\lambda = 1000$ m.

Antenna current I.	Working distance (Day)	Extreme distance of audibility (Day)
1 amp.	75 miles	200 miles
2	135	300
3	180	375
5	235	475
7	280	550
10	345	630
15	420	725
20	475	790
25	525	840
30	565	900
40	630	970
50	685	1,025
60	725	1,150

297. Good working distance and sending current for two stations with flat-top antennas 450 ft. high

Nautical miles	$\lambda = 1{,}000$ m.	$\lambda = 2{,}500$ m.	$\lambda = 3{,}750$ m.	$\lambda = 6{,}000$ m.
1,000	15 amp.	13.5 amp.	15 amp.	17 amp.
1,250	38	27	27	30
1,500	91	49	44	46
1,750	200	95	77	74
2,000	490	155	122	105
2,250	.....	245	200	160
2,500	.....	470	314	235
2,750	.....	.....	500	335
3,000	.....	.....	775	500

Bulletin of Bureau of Standards; Vol. VII, p. 315; 1911.

Working distances of 3,000 miles are covered by undamped wave stations with antennas approximately 600 ft. high and antenna currents of about 300 amperes.

298. Night transmission. While day transmission of radiotelegraphic signals is comparatively regular, night transmission is subject to very great fluctuations. At times night signals between two stations will be no stronger than those observed in the day time, while at other times sending sets of very moderate power and efficiency have been known to transmit signals several thousand miles. During the colder months of the year, night transmission can be depended upon to be considerably superior to day, with a fair degree of regularity. The cause of the increased night range is not definitely known. It has been thought by some authorities that it is due to a clearing up of the absorption supposed to exist in the upper atmosphere caused by the shorter light waves, and possibly cathode rays from the sun. Another explanation is that the absorption is fairly constant and that the increased received energy is due to reflection from the upper conducting layers of the atmosphere. This last view is supported by certain interference phenomena which cannot be entered into here, and by the fact that the abnormally strong night signals appear to pass over land almost as freely as over salt water, although the absorption in the day time is many times greater over land. That the normal

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energy is at times augmented in long-range night communication is shown by the fact that in many cases the received signals are stronger than would be expected from the geometric diminution of intensity with the distance, leaving absorption entirely out of account. It must also not be forgotten in this particular that observations show that the day condition is the stable one while the longer ranges covered at night show the irregularities which might be expected to come from irregular conditions of reflection.

RECEIVING CIRCUITS

299. Receiving antenna. The ordinary antenna may be used for receiving but for mitigating interference and static, some form of loop or loop antenna combination is used. (See Par. **280**). When an electric field of intensity E (Par. **269**) is produced on the ordinary antenna, there is an electromotive force in the antenna equal to Eh_1 where h_1 is the height of the receiving antenna from the earth to its center of capacity. For a coil antenna the equivalent height $h_2 = \frac{2\pi nA \cos \alpha}{\lambda}$, where A is the coil area, n the number of coil turns, α the angle between plane of coil and direction of propagation and λ the wave length.

300. Received antenna current. When tuned to resonance with the incoming waves, the received antenna current is from Eq. 16 (Par. **269**),

$$I_R = \frac{Eh_2}{R} \quad \text{(amp.)} \tag{20}$$

where R is the high-frequency resistance of the antenna system. This is strictly true only for incoming undamped oscillations. If the oscillations are damped, the expression becomes

$$I_R = \frac{Eh_2}{R\sqrt{1+\frac{\delta_1}{\delta_2}}} \quad \text{(amp.)} \tag{21}$$

where δ_1 and δ_2 are the logarithmic decrements of the sending and receiving systems.

301. Energy in the detector. Since most detectors used in radiotelegraphy are of high resistance, they are nearly always placed in separate circuits coupled directly or inductively to the antenna. The reason for placing them in separate circuits is practically the same as that for removing the spark from the antenna in the case of sending, since by varying the coupling the amount of energy consumed by the detector can be varied. When coupled so as to give the strongest response in the detector, approximately one-half of the total received energy is in the detector circuit; that is, the equivalent resistance added to the antenna circuit by coupling the detector circuit to it is approximately equal to the total original resistance (sum of radiation, ohmic and ground) of the antenna, with the detector circuit removed.

302. Types of receiving circuits. Figs. 87 and 88 show types of receiving circuits frequently used. The placing of a variable condenser in series

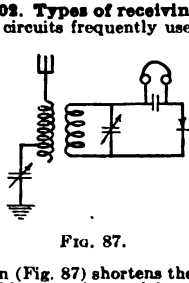


FIG. 87.

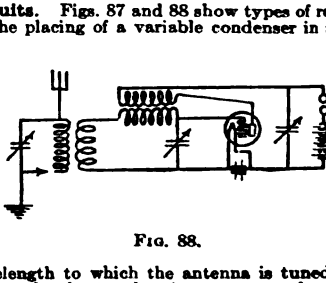


FIG. 88.

as in (Fig. 87) shortens the wavelength to which the antenna is tuned and enables it to be used for wave lengths shorter than its own natural period. Placing a condenser in parallel with the antenna inductance, as in (Fig. 88), increases the period of the antenna without adding additional inductance. In the above circuits the secondary circuit is tuned to the antenna and to the

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coming signal. (Fig. 87) with contact detector is used for damped wave ception, while (Fig. 88) with vacuum-tube detector is used for both damped id undamped waves.

DETECTORS

303. Types of detectors. A very large variety of detectors, coherer, agnetic, vacuum valve, and others, have been used in wireless telegraphy, it at present, for damped-wave telegraphy at least, the only detectors nerally employed in the better types of apparatus are various kinds of otifying contacts and vacuum detectors.

304. Contact rectifiers. The rectifiers most frequently consist of a ntact between a fine wire and some variety of mineral. Among the min- als frequently used are iron pyrites, galena, silicon, and molybdenite. In her forms, two crystals are used in contact, such as zinkite with chalco- yrite or bornite, or silicon with metallic arsenic.

The exact nature of the action of the contact rectifiers is not known. hey behave in general like high resistance thermoelements (though it is rtain that they are not thermoelements in the ordinary sense), the rectified rrent pulses produced by each wave-train being very approximately roportional to the square of the oscillatory current passing through the tector.

For detecting the direct-current pulses, **head telephones** of from 1,000 3,000 ohms resistance are ordinarily used. These are placed in shunt across e stopping condenser K (Fig. 83) of from 0.01 to 0.02 mf., which permits the scillatory currents to pass freely through it but stores up the direct-current ulses and discharges them through the telephone. If the spark at the send- g station is regular, the sound produced in the telephone is a pure musical ote. As a rough method of measuring the strength of signal, a resistance ox is frequently placed across the telephones and the resistance reduced ntil the signals just remain audible. The relative strength of the telephone rrent at various times can thus be determined from the law of shunts. or laboratory purposes a galvanometer is frequently used in place of the lephones.

THE RECEIVING OF CONTINUOUS OSCILLATIONS

305. Except where the oscillations are broken up into wave trains t the sending station, beat methods of reception are almost univer- lly used in radio telegraphy. For this purpose local oscillations differing ightly from the frequency of the incoming oscillations are produced in the ceiving circuit and the beat note resulting from the two sets of waves is ceived in the telephones. The pitch of the note is determined by the dif- rence in frequency between the two sets of oscillations.

306. Heterodyne reception. In this method the local oscillations are roduced in the receiving circuit by coupling it to an oscillating vacuum-tube rcuit. (See Fig. 90.) In this case the detector of the receiving circuit may e either a contact detector or a non-oscillating vacuum tube.

307. Autodyne reception. Fig. 88 shows an autodyne receiving circuit which the detecting bulb itself produces the oscillations. This method reception has the same sensitiveness as the terodyne method and has the advantage of ing less complicated. The secondary cir- uit is thrown out of resonance with the in- ming signals by an amount necessary to pro- uce the desired beat note in the telephones.

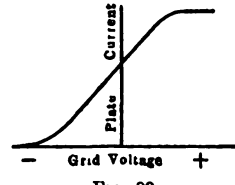


FIG. 89.

308. The three-electrode vacuum tube used as an amplifier, detector or oscillation nerator. The three electrodes are the fila- ent, grid, and plate. The important feature its operation is the control which the grid oltage exerts upon the electron current from he hot filament to the plate. This is shown the following grid voltage-plate current haracteristic curve.

309. When used as an amplifier (see Par. **308**) an alternating voltage applied between the grid and filament electrodes, which produces corre- onding variations in the plate current, or, in effect, superimposes an alter-

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nating current upon the steady plate current. If the operation takes plac upon the straight portion of the characteristic curve, the alternating plat current will have the same wave form as the grid voltage but will represe an amount of power many times that supplied to the grid. By means o transformer or resistance in the plate circuit of the tube, an alternating vol age a number of times greater than the original voltage can be obtained an applied to the grid circuit of a second tube. A number of tubes used cascade in this manner constitute an amplifier and can be designed to giv powerful amplification of either radio or audio frequency oscillations. Tw stage audio frequency amplifiers with transformer coupling can increase th audibility of a signal two hundred to nine hundred times.

310. As a simple detector the tube (Par. **308**) is ordinarily operated the lower bend of the characteristic. In this case the alternating-curr plate current is distorted, the positive half of the wave having a grea amplitude than the negative. Hence each wave train from a spark tra mitter acting upon the grid of the tube will produce an increase in the aver plate current or a current pulse. If, as is customary, the spark of t transmitter has a musical frequency, the current pulses will have the sa frequency and telephones included in the plate circuit will respond. sensitiveness the simple vacuum tube detector is about equal to the be crystal detectors but with the added advantage of stability.

311. When used as an oscillator (see Par. **308**) a circuit such as that Fig. 90 is employed in which a coil L' in the plate circuit is coupled back the grid circuit LC. If the coupling is sufficiently close and of the right sa then any accidental oscillation in t circuit LC, no matter how feeble, will reinforced by the EMF fed back into th circuit by the coil L' and the oscillati will build up to some constant amplitu determined by the tube and circuit co stants. The frequency of the oscillati will depend primarily upon the natu period of the LC circuit and can be vari from less than one per second to fi million or more per second. At t present time tubes have been develop for radio transmission which are capable of supplying power of the order a kilowatt apiece to the antenna.

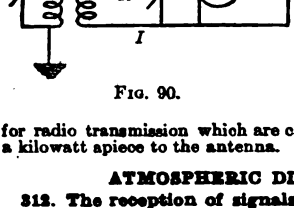


FIG. 90.

ATMOSPHERIC DISTURBANCES (STATIC)

312. The reception of signals is often interfered with by noises the telephones arising from electrical discharges and readjustment of pote tial in the atmosphere. These disturbances sometimes entirely prevent t reception of messages. They are especially severe on the longer wa lengths, above 6,000 meters. A vast number of experiments have be carried on in the past, in the hope of finding a remedy for this difficulty, b with only slight success. It has recently been discovered that the majori of the most troublesome disturbances observed in the eastern part of t United States comes from the southwest and can be largely eliminated b unidirectional receiving systems like the antenna loop combination men tioned in Par. **280**. In addition to this directive type there are near always local disturbances which at times become very severe.

HIGH-FREQUENCY MEASUREMENTS

313. Measurement of current. When it is desired to measure hig frequency currents quantitatively, shunted instruments in general are n satisfactory, since the value of the shunt ordinarily changes with the f quency. A form of hot-wire ammeter has been devised by Hartmann Braun in which the current is carried by a system of wires or bands symm rically placed in squirrel-cage arrangement so as to ensure a uniform distr bution of current among the bands. Each of the bands is of such dimensio that its high-frequency resistance does not differ from that for direct curre The indicating mechanism is attached to one of the bands. These instru ments have been made with current-carrying capacities up to 300 amper They are especially useful in the sending antenna when it is desired to kn

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rith accuracy the amount of energy radiated. For the measurement of very mall currents thermoelements are generally used.*

314. Wave meters. For determining the wave length of high-frequency ircuits wave meters are employed (Fig. 91). These consist essentially of a ircuit containing known inductance and capacity, one or both of which are ariable, and an indicating device such as a sensitive hot-wire milliwatt-neter which indicates by a maximum deflection when the wave meter is rought into resonance with he high-frequency circuit un-ler examination. The variable apacity in the wave meter sually consists of a semicircu-ar plate air condenser which s varied until the point of esonance is obtained. Fig. 92 hows a so-called **resonance urve** giving the relation be-ween the hot-wire milliwatt-neter deflection and the de-rees on the condenser. As was mentioned in Par. **267**, when the wave meter is in esonance with the circuit nder examination the product of the inductance and capacity n the wave meter circuit is qual to the product of the in-luctance and capacity in the ther. For the case of an

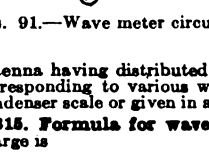


FIG. 91.—Wave meter circuit.

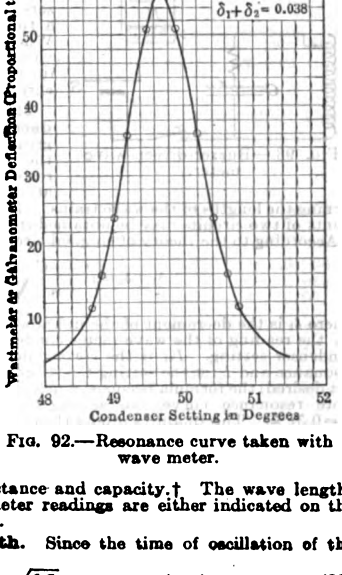


FIG. 92.—Resonance curve taken with wave meter.

antenna having distributed inductance and capacity.† The wave lengths corresponding to various wave-meter readings are either indicated on the condenser scale or given in a table.

315. Formula for wave length. Since the time of oscillation of the charge is

$$T = 2\pi\sqrt{LC} \quad \text{(sec.)} \qquad (21)$$

and $v = n\lambda$ and $T = 1/n$, then the wave length is

$$\lambda = v2\pi\sqrt{LC} \quad \text{or}$$

$$\lambda = 1.885\sqrt{LC}.\times 10^9 \quad \text{(meters)} \qquad (22)$$

where v is the velocity of light, L the inductance and C the capacity, all expressed in electromagnetic units. In place of the milliammeter a thermo-element and galvanometer or some other indicating device is sometimes used to indicate the current strength in the wave meter.

In order that the wave meter may be used for exciting receiving and other circuits at definite wave lengths, it is often connected to a buzzer circuit shown in Fig. 93. When the current from the cell s flowing through the inductance of the wave meter is broken at the vibrator of the buzzer B, the induced electromotive force charges the condenser of the wave meter. This charge oscillates back and forth through the inductance and condenser until

* For their construction and calibration, see Bulletin of Standards, Vol. VII, p. 304; 1911. Reprint, 158.

† See J. M. Miller, Scientific Paper No. 326 of the Bureau of Standards.

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the energy is dissipated in heat or radiation. As there is little resistance in the wave meter circuit the oscillations produced in this way are very feebly damped. If greater damping is desired, fine-wire resistance is introduced into the circuit at r. In order to eliminate the disturbing effects of the buzzer spark, a condenser K, of a few tenths of a microfarad, is placed around the coil of the buzzer. As the intensity of the oscillatory current in the wave meter depends on the magnitude of the direct current through the buzzer, this last should be of low resistance, about two or three ohms. Where great steadiness of high frequency current is desired for measurement purposes, buzzers specially built for this work having a tuning fork vibrator are satisfactory. When it is possible the oscillating vacuum-tube is used as an exciter since it produces an undamped sinusoidal current.

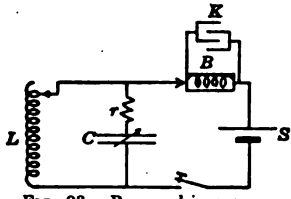


FIG. 93.—Buzzer-driven wave meter.

316. Measurement of logarithmic decrement. This measurement is of great importance since it makes possible the determination of the equivalent resistance of the circuits under consideration, and also gives information concerning the lengths of the wave trains. The value of the sum of the decrements of two circuits may be obtained from their resonance curve (Fig. 92).

According to the theory of coupled circuits,*

$$\delta_1+\delta_2=\pi\frac{C_m-C}{C_m}\sqrt{\frac{I^2}{I_m^2-I^2}} \qquad (22$$

where δ_1 is the decrement of the unknown circuit, δ_2 that of the wave meter, C_m the reading of the wave meter condenser for resonance, and C any other condenser setting. I_m is the corresponding current in the wave meter for resonance and I for the setting C. If great accuracy in the determination is not desired, the formula becomes much simplified if instead of plotting a complete resonance curve, the setting C of the condenser is so chosen that $I^2=0.5I^2_m$. The quantity under the radical becomes equal to unity and

$$\delta_1+\delta_2=\pi\frac{C_m-C}{C_m}. \qquad (24$$

If the decrement of the wave-meter circuit is known or can be calculated from the formula $\delta=R/2nL$, the decrement of the other circuit is at once obtained.

317. Logarithmic decrement (δ) of wave train and the approximate number of waves (N.) in the train before the amplitude falls to one-tenth of the maximum

δ	N	δ	N	δ	N	δ	N
1.0	3.5	0.4	7.0	0.1	24.0	0.04	58.0
0.8	4.0	0.3	8.5	0.08	30.0	0.03	78.0
0.6	5.0	0.2	12.5	0.06	39.0	0.02	116.0

Good tuning is not possible with less than fifteen waves in the train.

318. The high-frequency resistance of a circuit can be obtained by using a source of undamped oscillations as a power supply and reducing the current by known resistance. This method makes use of the fact that when the applied e.m.f. remains constant and an additional resistance is inserted in the circuit, the current is reduced by an amount depending on the value of the inserted resistance, or if I is the value of the current flowing in the circuit before inserting a known resistance R_1 and I_1 is the current value

* Fleming, J. "Principles of Electric Wave Telegraphy," p. 212., 1919.

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after the resistance R_1 is inserted, then the circuit high frequency resistance is given by $R = \frac{R_1}{\frac{I_1}{I} - 1}$.

319. For the determination of small equivalent resistances in high-frequency circuits, a method of substitution is frequently more satisfactory than the decrement method just mentioned. For instance, the equivalent resistance of a Leyden jar* is best obtained by substituting for the Leyden jar an air condenser theoretically free from resistance and of the same capacity as the jar, with sufficient known fine-wire resistance in series with it so that the current in the circuit is the same as when the Leyden jar was used. The limiting sizes of resistance wire for which the high-frequency resistance is the same as the direct-current resistance are given in Par. **320**. If the high-frequency resistance of an inductance is desired, the reduced current method is used.

320. Table of wire sizes
For which the high-frequency resistance will be less than 1 per cent. greater than direct-current resistance

Wave length (m.)	Constantan or advance wire		Manganin diameter (mm.)	Platinum diameter (mm.)	Copper diameter (mm.)
	Diameter (mm.)	Maximum current (amp.)			
100	0.30	3.5	0.29	0.13	0.006
200	0.46	4.5	0.40	0.20	0.045
300	0.57	5.5	0.50	0.27	0.09
400	0.66	7.0	0.60	0.30	0.10
600	0.83	8.0	0.75	0.37	0.15
800	0.98	10.0	0.88	0.42	0.20
1,000	1.10	11.5	0.99	0.50	0.21
1,200	1.20	12.5	1.10	0.57	0.22
1,500	1.30	14.0	1.21	0.63	0.26
2,000	1.52	17.0	1.38	0.73	0.30
3,000	1.80	24.0	1.62	0.80	0.33

Journ. Wash. Acad., Vol. II, p. 112; 1912.

321. High-frequency voltage. If the root-mean-square voltage is desired a static voltmeter is employed. The voltage which is ordinarily required is however the maximum voltage, since it is on this that the necessary insulation depends. This is best obtained by measuring the sparking distance between needle points or spheres placed in parallel with the part of the apparatus over which the voltage is desired. The table in Par. **318** shows the relation between sparking distance and maximum volts for brass spheres 1 cm. in diameter.

322. Spark voltage between brass spheres 2 centimeters in diameter, for various spark lengths

Spark length (in cm.)	Spark voltage	Spark length (in cm.)	Spark voltage
0.1	4,700	1	31,300
0.2	8,100	1.5	40,300
0.3	11,400	2	47,400
0.4	14,500	2.5	53,000
0.5	17,500	3	57,500
0.6	20,400	3.5	61,100
0.7	23,250	4	64,200
0.8	26,100	4.5	67,200
0.9	28,800	5	69,800

* Bulletin of the Bureau of Standards, Vol. IX, p. 73; 1912. Reprint 190.

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SECTION 22

MISCELLANEOUS APPLICATIONS OF ELECTRICITY

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SECTION 22

MISCELLANEOUS APPLICATIONS OF ELECTRICITY

ELECTRIC SHOCK AND RESUSCITATION

1. Report of Commission on Resuscitation from Electric Shock. The rules for resuscitation of victims of electric shock, as set forth in Par. **2**, **3** and **4**, were recommended in 1912 by the Commission on Resuscitation from Electric Shock, in the report tendered to the National Electric Light Association. This commission, under the chairmanship of Dr. W. B. Cannon of Harvard University, represented the American Medical Association, the American Institute of Electrical Engineers and the National Electric Light Association. The rules are here reproduced verbatim in Par. **2**, **3** and **4** by permission of the latter organization; copies of the rules can be had at a very nominal cost by application to the Secretary, 29 West 39 St., New York. Also see "Report of Committee on Accident Prevention;" Trans. N. E. L. A., June, 1914, Thirty-seventh Convention; pp. 630–654.

An important note accompanying the rules states that the prone-pressure method of artificial respiration described (Sec. III below) is equally applicable after clearing the mouth of froth, to resuscitation of the drowned, and also to cases of suspended respiration due to inhalation of gases or to other causes.

2. Treatment for electric shock.* An accidental electric shock usually does not kill at once, but may only stun the victim and for a while stop his breathing.

The shock is not likely to be immediately fatal, because:

(a) The conductors may make only a brief and imperfect contact with the body.

(b) The skin, unless it is wet, offers high resistance to the current.

Hope of restoring the victim lies in prompt and continued use of artificial respiration. The reasons for this statement are:

(a) The body continuously depends on an exchange of air, as shown by the fact that we must breathe in and out about fifteen times a minute.

(b) If the body is not thus repeatedly supplied with air, suffocation occurs.

(c) Persons whose breathing has been stopped by electric shock have been reported restored after artificial respiration has been continued for approximately 2 hr.

The Schaefer or "prone pressure" method of artificial respiration, slightly modified, is illustrated and described in the following resuscitation rules. The advantages of this method are:

(a) Easy performance; little muscular exertion is required.

(b) Larger ventilation of the lungs than by the supine method.

(c) Simplicity; the operator makes no complex motions and readily learns the method on first trial.

(d) No trouble from the tongue falling back into the air passage.

(e) No risk of injury to the liver or ribs if the method is executed with proper care.

Aid can be rendered best by one who has studied the rules and has learned them by practice on a volunteer subject.

3. Instructions for resuscitation. Follow these instructions even if victim appears dead.

I.—BREAK THE CIRCUIT IMMEDIATELY

(a) With a single quick motion separate the victim from the live conductor. In so doing avoid receiving a shock yourself. Many have, by their carelessness, received injury in trying to disconnect victims of shock from live conductors.

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OBSERVE THE FOLLOWING PRECAUTIONS

(a) Use a dry coat, a dry rope, a dry stick or board, or any other *dry non-conductor* to move either the victim or the wire, so as to break the electrical contact. Beware of using metal or any moist material. The victim's loose clothing, if dry, may be used to pull him away; do not touch the soles or heels of his shoes while he remains in contact—the nails are dangerous.

(b) If the body must be touched by your hands, be sure to cover them with rubber gloves, mackintosh, rubber sheeting or dry cloth; or stand on a dry board or on some other dry insulating surface. If possible, use only *one* hand.

If the victim is conducting the current to ground, and is convulsively clutching the live conductor, it may be easier to shut off the current by lifting him than by laying him on the ground and trying to break his grasp.

(c) Open the nearest switch, if that is the quickest way to break the circuit.

(d) If necessary to cut a live wire, use an ax or a hatchet with a dry wooden handle, or properly insulated pliers.

II.—SEND FOR THE NEAREST DOCTOR

This should be done without a moment's delay, as soon as the accident occurs, and while the victim is being removed from the conductor.

III.—ATTEND INSTANTLY TO VICTIM'S BREATHING

(a) As soon as the victim is clear of the live conductor, quickly feel with your finger in his mouth and throat and remove any foreign body (tobacco, false teeth, etc.). Then begin artificial respiration at once. Do not stop to loosen the patient's clothing; *every moment of delay is serious.*

(b) Lay the subject on his belly, with arms extended as straight forward as possible, and with face to one side, so that the nose and mouth are free for breathing (see Fig. 1). Let an assistant draw forward the subject's tongue.



FIG. 1.—Inspiration; pressure off.

If possible, avoid so laying the subject that any burned places are pressed upon.

Do not permit bystanders to crowd about and shut off fresh air.

(c) Kneel straddling the subject's thighs and facing his head; put the palms of your hands on the loins (on the muscles of the small of the back), with thumbs nearly touching each other, and with fingers spread over the lowest ribs (see Fig. 1).



FIG. 2.—Expiration; pressure on.

(d) With arms held straight, swing forward slowly so that the weight of your body is gradually brought to bear upon the subject (see Fig. 2). This operation, which should take from two to three seconds, *must not be violent*—internal organs may be injured. The lower part of the chest and also the abdomen are thus compressed, and air is forced out of the lungs.

(e) Now *immediately* swing backward so as to remove the pressure, but leave your hands in place, thus returning to the position shown in Fig. 1

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Through their elasticity, the chest walls expand and the lungs are thus supplied with fresh air.

(f) After 2 sec. swing forward again. Thus repeat deliberately twelve to fifteen times a minute the double movement of compression and release—a complete respiration in 4 or 5 sec. If a watch or a clock is not visible, follow the natural rate of your own deep breathing—swinging forward with each expiration, and backward with each inspiration.

While this is being done, an assistant should loosen any tight clothing about the subject's neck, chest, or waist.

(g) Continue artificial respiration (if necessary, 2 hr. or longer), *without interruption*, until natural breathing is restored, or until a physician arrives. Even after natural breathing begins, carefully watch that it continues. If it stops, start artificial respiration again.

During the period of operation, keep the subject warm by applying a proper covering and by laying beside his body bottles or rubber bags filled with *warm* (not hot) water. The attention to keeping the subject warm should be given by an assistant or assistants.

(h) *Do not give any liquids whatever by mouth until the subject is fully conscious.*

4. First care of burns. When natural respiration has been restored, burns, if serious, should be attended to until a doctor comes.

A raw or blistered surface should be protected from the air. If clothing sticks, do not peel it off—cut around it. The adherent cloth, or a dressing of cotton or other soft material applied to the burned surface, should be saturated with picric acid (0.5 per cent.). If this is not at hand, use a solution of baking soda (one teaspoonful to a pint of water), or the wound may be coated with a paste of flour and water. Or it may be protected with a heavy oil, such as machine oil, transformer oil, vaseline, linseed, castor or olive oil. Cover the dressing with cotton, gauze, lint, clean waste, clean handkerchiefs, or other soft cloth, held lightly in place by a bandage.

The same coverings should be lightly bandaged over a dry, charred burn, but without wetting the burned region or applying oil to it.

Do not open blisters.

5. Physiology. Victims of severe electric shock may suffer from a cessation of natural breathing or from an impairment of their heart action. In cases where the latter condition amounts to a complete stoppage of the regular expansion and contraction of the heart, and where the organ merely fibrillates or quivers there appears at present to be no adequate relief, and death follows speedily. It is, however, extremely difficult to discriminate accurately between the fibrillating heart and one in which the action has been greatly diminished; in the latter case some method of artificial respiration may prove successful, hence the correct assumption in all cases should be the safe one, and alleviatory measures should be undertaken.

Artificial respiration may be successful in cases of suspended respiration and also in cases of impaired heart action. The weakened heart detracts from an already impaired respiration and may completely annul it. In turn, the absence of breathing reacts upon the heart and completely quells its feeble beating. If, through any combination of these two factors, the brain cells are deprived of oxygen for longer than 10 min., recovery is impossible in almost all cases, hence the necessity for speedy action.

6. Choice of Schaefer method of artificial respiration. The Schaefer method was chosen as a result of experiments which were performed upon living subjects and upon completely curarized animals. To approximate the toneless condition of unconscious persons, the test subjects were put in a state of apnœa following a period of enforced breathing which lasted several minutes. Experiments to determine the elasticity of the toneless body were made upon cadavers. It was also found that the Schaefer method is greatly improved by the extension of the subjects' arms forward.

7. Mechanical respiratory devices now upon the market, operate by oxygen pressure, the inspiration being made under pressure and the expiration being accomplished by suction. The inspiratory gas may be either pure oxygen or a mixture of oxygen and air.

8. The pulmotor* differs from other types of commercial apparatus in

* Report of Committee on Resuscitation from Mine Gases; Technical Paper 77, U. S. Bureau of Mines, 1914.

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hat the reversals of respiratory flow are controlled by the mechanism of the nstrument. It consists of a closely fitting face mask, a source of oxygen nd the reversing mechanism. It is so constructed that inspiration ceases hen the entering gas encounters sufficient resistance to cause the mechanism o reverse and expiration to begin. This reversal is intended to result from he resistance due to completely filled organs of respiration.

Records of cases in which the pulmotor has been used are not convincing hat it is superior to or even the peer of the Schaefer method, properly applied. t is claimed that two factors interfere with its successful use. In the first lace, as the reversal of respiratory flow is controlled automatically, there s no assurance that inspiration may not be changed to expiration too soon, s the result of obstructions in the air passages which act upon the reversing nechanism before a complete ventilation has taken place. It is possible to vercome this defect by manually controlling the operating mechanism and hus extending the inspiration to the proper limit. The second factor s observed in connection with expiration by suction. The finer bronchi- les are provided with no cartilages to stiffen them, and when air is ucked from the trachea and from the larger bronchi, these bronchioles are ikely to close before air can be drawn through them from the alveoli. Furthermore, during the process of suction, the walls of the bronchioles and lveoli may collapse and stick together, rendering the subsequent inspiration nore difficult, and further decreasing the ventilation. The escape of air nto the stomach has been observed to cause movements of the thorax which closely simulate respiration, while actually no air enters or leaves the bronchial tree.

9. Pharyngeal insufflation* is a method of mechanically applied artificial respiration which has been recommended by the Commission on Resuscitation as a satisfactory supplement to the prone-pressure (Schaefer) method in cases of suspended respiration. Inspiratory air enters through a tube inserted in the pharynx, and so constructed as to conform to the human anatomy in order to prevent the escape of air through the mouth and nasal passages. An oxygen tank or a pair of foot bellows supplies the necessary pressure, and reversals of respiration are controlled by the operation of a respiratory valve, which can be conveniently held and operated with one hand. This valve is essentially a three-way cock which, when the valve s in one position, will furnish communication between the source of pressure and the pharyngeal tube, and when in another position, will allow a free expiration to the atmosphere while the pressure lead is shut. In case a specially constructed pharyngeal tube is not available, it is possible to use a close-fitting mask, provided with a tube for connection to the valve. Air is prevented from entering the stomach by placing a heavy weight upon the abdomen; this may be reinforced by a belt, though a belt alone should not be depended upon. A weight upon the abdomen may likewise render good service to a failing circulation by increase of blood pressure. In cases where t is found impracticable to use weights, the air may be drained from the stomach through a tube which furnishes communication between the stomach and the outside air. This stomach tube passes through the pharyngeal tube, but interferes in no way with the process of insufflation. This machine is light and can be constructed at relatively small expense.

10. Current tolerance of the human body. It was announced many years ago by Tesla, Elihu Thompson and D'Arsonval, that alternating currents of high frequency produced little sensation when passed through the human body, compared with alternating currents of low frequency and equal strength. Tests have been made to determine the "tolerance current" of various individuals at several frequencies. The tolerance current was arbitrarily assumed as the limiting current strength which the subject could take through his arms and body, without marked discomfort or distress.

It was found that for each individual, there is a marked increase of current strength which may be tolerated, as the frequency is increased from 11,000 to 100,000 cycles per sec. A man can tolerate only about 30 milliamperes at 11,000 cycles per sec. but can tolerate nearly half an ampere at 100,000 cycles per sec.† Although the tolerance current was found to increase

* See *Journal of American Medical Association*, 1913, Vol. LX, p. 1407.

† Kennelly, A. E. and Alexanderson, E. F. W. "The Physiological Tolerance of Alternating-current Strengths;" *Electrical World*, 1910, Vol. LVI, page 154.

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very rapidly above 11,000 cycles per sec., the increase between 60 cycles and 11,000 cycles was much less rapid, ranging from about 5 milliamperes at 60 cycles to 30 milliamperes at 11,000 cycles.

ELECTRIC HEATING AND COOKING

BY E. N. LIGHTFOOT

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11. Sources of electric heat. Some part of the energy in any electric circuit is converted into heat. All of the electrical energy may be converted into heat by means of the electrical heater. As electrical energy is a transient form of energy, the operation of an electric heater implies the simultaneous conversion of a primary form of energy into electricity. The usual primary forms of energy or sources of electricity are (1) the energy contained in fuel and (2) the energy of falling water. The development of heat in an electric heater necessitates, under usual conditions, the consumption of fuel or the use of water power, at practically the same moment that the heater is in operation.

12. Comparison with fuels. The characteristics of electric heating which distinguish it from other methods of heating, and from which all of its advantages arise, are that the heat may be developed (*a*) at a location remote from the point at which combustion takes place; (*b*) at any desired temperature best suited to the work, *i.e.*, independent of the temperature of combustion, (*c*) at a high efficiency, or economy of heat units, and (*d*) at a high degree of concentration, *i.e.*, at a high energy density. Fuel may be burned, but instead of being burned inefficiently and locally at each point where heat is developed, it is burned efficiently and in bulk at a central station where the various problems and disadvantages involved in the supply and combustion of fuel and disposal of ashes, dirt and combustion gases can be handled best. The product of the central station, electrical energy, may be looked upon from the heating standpoint as a perfectly refined fuel, 100 per cent. heat.

The direct use of solid fuel or liquid fuel is usually justified where low cost of raw fuel is the predominant factor, as in large scale industrial processes, and in heating buildings. Gas fuel has gone through a process of refining which adds to its cost per heat unit and improves its efficiency of application. It still retains all disadvantages inherent in the combustion process, such as high temperature, fire risk, and vitiation of the atmosphere.

13. Advantages of electric heating. Electric heating definitely removes all limitations due to the presence of combustion at the point where heat is desired. The presence of combustion is detrimental rather than helpful in practically all of the innumerable heating applications in industry and in the home. Electric heating permits development of the heat at any temperature required or best suited to the work, from the lowest temperatures encountered, up to approximately 2,000 deg. fahr. for heaters employing metallic resistors, and to higher temperatures for heaters employing non-metallic resistors, or the electric arc. Its freedom from combustion limitations, its ability to produce any temperature required and its high efficiency of application, make electric heating the logical means of heating where the following conditions exist:

1. Where the cost of electrical energy is less than the cost of fuel, due to the greater efficiency of application of the electric heater:—Soldering tools, glue pots, chocolate warmers, plate warmers, packaging machines, flat irons, heating pump and valve houses.

2. Where other items of cost such as labor of attendance, investment charges, decreased waste or spoilage, make the overall cost of the operation less:—Japanning ovens, linotype pots, metal melting and heating furnaces, matrix presses.

3. Where increased rate of production makes the cost per unit of production less:—Core ovens, bread ovens, packaging machines, heating pipe lines, soldering tools, printing presses.

4. Where improvement in quality of the product warrants the increase in cost:—Japanning ovens, embossing presses, impregnating tanks, moulding presses, drying boxes.

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5. Where sufficient collateral advantages are realized, such as decreased fire hasard, greater safety, improved working conditions, etc.:—Celluloid heaters, paper embossing, glue pots, soldering irons, sterilizers, urns, water heaters, japanning ovens, blue print driers.

6. Where electric heating is so peculiarly well suited to the work that comparison of costs need not be considered, or where the use of fuel is inappropriate, impracticable or impossible:—Automobile and air plane engines, incubating rooms, crane cabs, sprinkler systems, drying electrical machinery and apparatus, pipe organs, lightning arrestors, seed sprouting.

14. Heat contents of fuels and of electricity.

1 lb. of coal contains approximately 12,000 B.t.u.
1 lb. of wood contains approximately 7,000 B.t.u.
1 lb. of gasoline contains approximately 20,000 B.t.u.
1 lb. of steam contains approximately 1,000 B.t.u.
1 cu. ft. of natural gas contains approximately 1,000 B.t.u.
1 cu. ft. of producer gas contains approximately 140 B.t.u.
1 cu. ft. of manufactured gas contains approximately 600 B.t.u.
1 kwh. of electricity contains approximately 3,412 B.t.u.

15. Efficiency of application. The above figures represent approximately the potential heat energy in the fuel. The useful heat secured depends upon the efficiency of application, which is lowest with solid fuels and highest with electricity. The efficiency of the household range has been found as low as 2 per cent. The efficiency of translation of electricity into heat is 100 per cent.; the efficiency of application of electric heating is variable but always higher than the efficiency of combustion heating and in some cases approaches close to 100 per cent. Where the cost of electricity is higher than the cost of fuel for a given application, it is usually due to the losses encountered in the process of securing electricity from fuel (*i.e.* to the low efficiency of the steam engine or turbine) causing a high cost per heat unit or kwh.

16. Comparisons between Manufactured Gas and Electricity

Application	Watt hours of electricity equivalent to 1 cu. ft. of gas containing 600 B.t.u. or 176 watt-hr.	Relative efficiency in favor of electricity	Approximate rate per kwh. at which cost of electrical energy equals cost of gas at $1.00 per 1,000 cu. ft.* cents
Cooking stove top	40.0	4.4 to 1	2.5
Baking oven	25.2	7.0 to 1	4.0
Water heating	12.6	1.4 to 1	0.8
Household range	30.5 to 61.0	2.9 to 1 to 5.8 to 1	1.67 to 3.3
Fireless cooker	14.3	12.3 to 1	7.0
Type metal melting (linotype pot)	40.0	4.4 to 1	2.5
Industrial ovens, baking, drying, japanning, etc.	50.0 to 110.0	1.6 to 1 to 3.5 to 1	0.9 to 2.0

* Note that these rates are based upon fuel cost only and do not take into consideration the advantages of electric heating which at higher rates may still be more economical or preferable for other reasons.

The data given in the above table are compiled from various sources which are not always in agreement, and therefore can not be accepted as accurate nor applicable to all conditions, but are considered as being approximately correct under average conditions for the purpose of making comparisons upon a fuel cost basis.

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17. Measurement of heat quantities. Quantity of heat is usually measured by the British thermal heat unit, defined as the amount of heat absorbed by one pound of water when it increases in temperature one degree fahrenheit. In electric heating problems it is usually more convenient to use electrical terms and measure quantities of heat in watt-hours, and the rate at which heat is produced, in watts.

Quantity.—One watt-hour = 3.412 B.t.u., or is equivalent to raising the temperature of 3.412 lb. of water through 1 deg. fahr.

Rate.—One watt = 3.412 B.t.u. per hour, or is equivalent to heating water at the rate of 3.412 pounds one deg. fahr., per hour.

Where there is a well-established art, and constants and reference tables are based on B.t.u. measurements, as in heating buildings, the calculations may be carried through on the B.t.u. basis and translated into electrical terms as above. See Par. on room heating.

18. Analysis of heat requirements. The total heat requirements of any application may be analysed into the following five factors: (I) Radiation, (II) convection, (III) conduction, (IV) absorption, and (V) change of state.

19. Radiation of heat is similar to the radiation of light. It is projected from the surface of a body through any medium that is transparent to it, such as clear air. When it meets a body that is opaque to it, it is partly absorbed by the opaque body, and the absorbed radiation appears as heat upon the surface of that body. *The rate of radiation is proportional to* $T^4 - t^4$ (Stefan-Boltzman Law), where T is the absolute temperature of the sending surface and t is the absolute temperature of the receiving surface. The rate at which a black body surface radiates heat into rooms at 68 deg. fahr. is given in Fig. 3. Most surfaces radiate less heat than black body

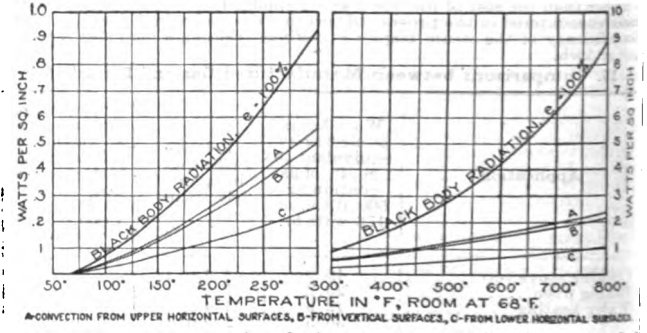


FIG. 3.—Connection losses from horizontal and vertical surfaces, and black body radiation.

surfaces. Par. **21** gives the watts radiated by typical surfaces expressed in per cent. (emissivity constant) of the watts radiated by a black body surface. Radiation increases as the fourth power of the absolute temperature; it therefore becomes relatively enormous at high temperatures, and permits extremely high ratings in watts per sq. in. of radiating surface, for such constructions as bare nickel-chromium resistors operating at 1,000 to 2,000 deg. fahr. and radiating directly from the resistor surface. Such heaters are therefore termed radiant heaters.

20. Convection. The surface of a heated body in contact with air (or other gases or liquid), heats the air in immediate contact with it. The film of air, in heating, expands to a lower specific gravity than the cooler air around it and therefore tends to rise. Thus a natural circulation is set up, the warm air rising from the area of contact with the hot surface and being displaced by the cool air flowing in from below. The rate at which heat is carried off by convection in air is shown in curves, Fig. 3, for flat surfaces in three positions, (*A*) upper horizontal surface of the heated body, (*B*) vertical surfaces and (*C*) lower surface.

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In heating water advantage is taken of convection by applying the heat near the bottom of the body of water, thus distributing the heat throughout the mass by convection. Similarly in heating rooms, ovens, etc., heaters if placed near the floor, will diffuse the heat more uniformly. As convection currents always carry heat upward, not downward, the heater must be placed lower than the body or zone which is to be heated by convection. Enforced movement of air or water will considerably increase the amount of heat carried off by convection.

21. Relative Radiating Power or Emissivity of Various Surfaces

Surface	Emissivity constant "e" in per cent. of radiation from a black body surface	Surface	Emissivity constant "e" in per cent. of radiation from a black body surface
Black body	100 (*j*)	Wrought iron, polished	23 (*hk*)
Lampblack	100 (*hk*)	Mercury	23 (*h*)
Water	100 (*h*)	Cast iron, bright	22 (*j*)
Glass	90 (*hk*)	Zinc, polished	19 (*hk*)
Copper, oxidised	72 (*j*)	Lead, clean	19 (*k*)
Cast iron, oxidised	62 (*j*)	Steel, polished	17 (*h*)
Aluminum paint on cast iron	50 (*j*)	Copper, natural surface	12 (*k*)
Lead, tarnished	45 (*k*)	Brass, highly polished	7 (*hk*)
Cast iron, polished	25 (*hk*)	Silver, highly polished	3 (*hjk*)

Authorities.—(*j*) Langmuir. (*h*) Kent's Mechanical Engineers Pocket Book. (*k*) Frederick Dye, "A Practical Treatise on Steam Heating," published by Spon, London, 1901.

22. Conduction, flow of heat and heat potential. Conduction applies to the transfer of heat, molecule to molecule, through a body, and is analogous to the conduction of electricity. Heat flows by conduction from a point of high temperature to a point of low temperature. Temperature is heat potential, analogous to electrical potential. Temperature difference, or gradient, is analogous to electrical voltage. The rate of heat flow is proportional to the thermal conductance and inversely proportional to the thermal resistance of the path through which heat flows.

Heat flow in watts = Temperature Gradient × thermal conductance, or
Heat flow in watts = Temperature Gradient/thermal resistance.

The table, Par. **24**, gives for various materials, the thermal conductivity or heat flow expressed in watts (column 2, watts per square inch; column 4, watts per square foot) through one inch thickness of that material for a temperature gradient of one deg. fahr. The reciprocals will give thermal resistivity expressed in deg. fahr. gradient per watt of heat flow. The total thermal resistance of a path is the sum of the individual resistances of the sections of the path that are in series.

23. Heat insulators; construction of insulating walls. Materials which are such poor conductors of heat that they are used to impede the flow of heat are termed heat insulators. Their effectiveness is relatively much less than the effectiveness of electrical insulators and the best of heat insulators will transmit an appreciable amount of heat. This indicates the importance of providing proper heat insulation, particularly where energy costs are high, and also the necessity of allowing for the heat conducted through the insulation. In designing walls for such structures as ovens, materials of the lowest possible thermal conductivity should be used. Walls of ordinary brick sacrifice thermal insulation for structural strength, but they conduct heat at such a high rate that for prevailing energy costs they are not economical structures. A preferred wall construction consists of the best heat insulators retained between two sheets of metal. The walls should be so constructed as to present the least possible section of through metal, that is, metal which extends through from the hot zone to the cold one. The effect of through metal may be appreciated by the fact that a ⅛-in. bolt will transmit approximately as much heat as a square foot of good heat insulating material.

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24. Thermal Conductivities of Different Substances

Material	Watts per square inch for gradient of 1 deg. fahr. per in. of thickness	Material	Watts per square foot for gradient of 1 deg. fahr. per in. of thickness
Silver, 212 deg. fahr.	5.9 (a)	Fire-brick, 900 deg. fahr.	1.19 (b)
Copper, 212 deg. fahr.	5.4 (a)	Brick, red building	2.96 (b)
Aluminum, 212 deg. fahr.	2.9 (a)	Asbestos, 200 deg. fahr.	0.387 (e)
Zinc, 212 deg. fahr.	1.5 (a)	Asbestos, 300 deg. fahr.	0.412 (e)
Brass, 212 deg. fahr.	1.5 (a)	Asbestos, 400 deg. fahr.	0.426 (e)
Tin, 212 deg. fahr.	0.84 (a)	Asbestos, air cell, 200 deg. fahr.	0.183 (b)
Iron, wrought, 212 deg. fahr.	0.84 (a)	Asbestos, air cell, 400 deg. fahr.	0.199 (b)
Iron, cast, 212 deg. fahr.	0.64 (a)	Asbestos Fire Felt, 400 deg. fahr.	0.108 (b)
Steel, soft	0.66 (a)	Hair-felt	0.102 (b)
Steel, hard	0.37 (a)	Mica	0.727 (j)
Lead, 212 deg. fahr.	0.45 (a)	Mineral wool	0.14 (b)
Nickel, 70 deg fahr.	0.84 (a)	Non-pareil	0.145 (b)
Mercury, 125 deg fahr.	0.112 (a)	Wood, perpendicular to grain	0.307–0.423 (c)
Marble	0.033 (a)	Sawdust	0.13 (c)
Pasteboard	0.0027 (a)	Sand, coarse	0.109 (c)
Paper	0.0018 (j)	Magnesia, 85 per cent.	0.132 (c)
Slate	0.021 (a)	Silocel powder, 300 deg. fahr.	0.10 (d)
Porcelain	0.028 (a)	Silocel powder, 400 deg. fahr.	0.135 (d)
Masonry	0.034 (b)	Silocel powder, 500 deg. fahr.	0.174 (d)
Glass	0.0065 (a)	Silocel powder, 600 deg. fahr.	0.197 (d)
Paraffine wax	0.0035 (c)	Silocel powder, 700 deg. fahr.	0.221 (d)
Rubber	0.0028 (b)	Infusorial earth, loose, 200 deg. fahr.	0.158 (e)
Gutta Percha	0.0028	Infusorial earth, loose, 300 deg. fahr.	0.166 (e)
Concrete	0.013 (a)	Infusorial earth, loose, 400 deg. fahr.	0.176 (e)
Water	0.008 (c)	Infusorial earth, loose, 600 deg. fahr.	0.186 (e)
Alcohol	0.0029	Air, not in motion, 68 deg. fahr.	0.051
Petroleum	0.0021 (c)	Air, not in motion, 212 deg. fahr.	0.061
Glycerine	0.0034		

Authority.—(a) Smithsonian Physical Tables. (b) Randolph. (c) Mark's Mechanical Engineer's Hand Book. (d) Manufacturer. (e) Nusselt. (j) Langmuir.

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25. Effect of joints. The figures given in Par. **24** are for materials that are continuous. A joint between materials will add thermal resistance, usually a very considerable amount, to the flow of heat across it. Thermal resistance at the joint may be reduced by machining the surfaces and by pressure, *i.e.*, by making the mechanical contact more intimate.

26. Absorption. Materials have capacity for heat. They absorb heat when increasing in temperature, and deliver heat when decreasing in temperature, but the amount of heat contained by them is constant when the temperature is constant, unless there is a change of state as noted below. Therefore the tendency of absorption is to retard heating and to retard cooling. Absorption is particularly important during the period of heating up from room temperature to working temperature, and in conveyor processes, where the material or work passing through absorbs a large amount of heat per hour. To decrease the time of heating up from room temperature to working temperature a higher wattage may be applied until working temperature is reached, whereupon the wattage is reduced. See Par. **29**.

27. Change of state. Change of state from solid to liquid requires supplying the latent heat of fusion. Similarly change of state from liquid to gas or vapor requires supplying the latent heat of evaporation. See Par. **29**. If a liquid is exposed to air so that evaporation takes place, the latent heat of evaporation must be supplied. Barker, in "Heating and Ventilation," gives the following data on rate of evaporation and total heat loss from each square foot of exposed water surface in quiet air at 52 deg. fahr. and 86 per cent. humidity.

At 135 deg. fahr., 0.5 lb. per hr., total heat loss 750 B.t.u. per hr. or 220 watts.

At 157 deg. fahr., 1.0 lb. per hr., total heat loss 1,350 B.t.u. per hr. or 396 watts.

At 180 deg. fahr., 2.0 lb. per hr., total heat loss 2,450 B.t.u. per hr. or 720 watts.

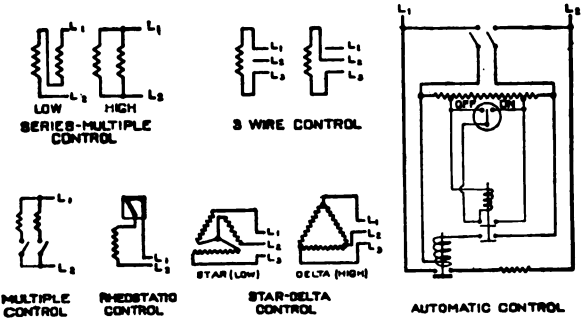


FIG. 4.—Methods of regulating heat.

28. Limits in temperature; energy density. The temperature at which essential parts of the heater deteriorate and lose their effectiveness (as by oxidation of the resistor, or dehydration of mica insulation) determines the limit in safe operating temperature. The temperature of the heater rises above the temperature of its environment (room temperature, metal temperature, temperature of machine or apparatus to which heater is applied) until it establishes a temperature gradient that will deliver heat to the environment at a rate measured by the watts absorbed by the resistor. The permissible temperature of the process can be raised or the temperature of the heater can be lowered by reducing the temperature gradient in either of two ways: (1) Decreasing the thermal resistance within the heater and between the heater and the work or (2) by increasing the effective heater area so as to operate at a lower energy density, *i.e.*, at less watts per sq. in. of active heater surface.

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29. Heat Capacities of Various Materials in Watt-hours per Lb.

Solids	Watt-hours per pound absorbed for each deg. fahr. increase	Watt-hours per pound to supply latent heat of fusion	Liquids, etc.	Watt-hours per pound absorbed for each deg. fahr. increase	Watt-hours per pound to supply latent heat of fusion
Aluminum	0.065 (*a*)	42.7 (*a*)	Alcohol	0.176 (*a*)	148.3 (*a*)
Brass	0.026 (*a*)	27.7 (*i*)	Oil, machine	0.117 (*a*)	.....
Bronze	0.031 (*c*)	.....	Oil, petroleum	0.149 (*a*)	.....
Copper	0.028 (*a*)	23.4 (*a*)	Mercury	0.0096 (*a*)	36.1 (*a*)
Iron, cast, gray	0.035 (*a*)	12.8 (*a*)	Tin (molten)	0.015 (*a*)	.....
Iron, wrought	0.034 (*a*)	.....	Lead (molten)	0.012 (*a*)	.....
Lead	0.009 (*a*)	2.9 (*a*)	Petroleum products	0.147	.....
Nickel	0.033 (*a*)	2.6 (*a*)	Water*	0.293 (*g*)	285.0 (*f*)
Solder	0.012 (*a*)	6.4 (*a*)	Steam	0.123 (*a*)	.....
Tin	0.016 (*a*)	7.8 (*a*)	Air	0.0697 (*a*)	.....
Zinc	0.027 (*a*)	15.6 (*a*)	.....	.....	.....
Asbestos	0.057 (*a*)	.....	.....	.....	.....
Glass	0.057 (*g*)	.....	.....	.....	.....
Ice	0.148 (*g*)	42.2 (*f*)	.....	.....	.....
Lava	0.059 (*c*)	.....	.....	.....	.....
Masonry (brick)	0.059 (*h*)	.....	.....	.....	.....
Paraffin	0.204 (*a*)	19.5 (*a*)	.....	.....	.....
Porcelain	0.075 (*c*)	.....	.....	.....	.....
Sand	0.057 (*h*)	.....	.....	.....	.....
Wood, hard	0.167 (*c*)	.....	.....	.....	.....

Authority.—(*a*) Smithsonian Physical Tables. (*c*) Mark's Mechanical Engineers Hand Book. (*f*) Machinery Hand Book. (*g*) Regnault, Kent's Mechanical Engineer's Pocket Book. (*h*) Kent's Mechanical Engineer's Pocket Book. (*i*) Richards, Metallurgical Calculations.

* To evaporate 1 lb. of water from and at 212 deg. fahr. requires 285 watt hours to supply the latent heat of evaporation.

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30. Heat balance; final temperature. When current flows through he resistor of an electric heater, heat is developed immediately in the resistor it a rate measurable in watts. The temperature of the resistor increases, stablishing a temperature gradient above the surrounding parts, which radient causes heat to flow from the resistor to these parts. Each point hroughout the structure receives heat from points of higher temperature, bsorbs some of the heat energy in increasing its own temperature and conducts the heat to adjacent points of lower temperature. When the surface of the heater rises in temperature it dissipates heat into the atmosphere or o the surrounding materials. The surface at first cannot dissipate all the eat that reaches it from the interior. Therefore its temperature rises and oncurrently its ability to dissipate heat into the atmosphere increases. The surface temperature continues to rise until the rate at which it dissipates eat into the atmosphere equals the rate at which it is receiving heat. While he heater rises in temperature it is absorbing heat energy. When the eater temperature stops rising and becomes constant, it is thermally balanced. To estimate the wattage required to produce a constant temperature, the heat losses at that temperature should be calculated. The total eat requirements analyzed into the five factors as above and measured in watts will give the required heater rating in watts.

31. Heater construction. The requirement for all materials is continuous life at operating temperatures. Nickel-chromium alloy resistors are the most widely used of the metallic resistors because of their resistance to deterioration at high operating temperatures. They are capable of withstanding temperatures up to approximately 2,000 deg. fahr., but usually operate at lower temperatures because of limitations in other parts of the structure.

The insulation for most heater applications is mica. Mica dehydrates and loses its insulating value at temperatures that limit the external heater emperature to about 800 to 1,100 deg. fahr. For higher temperatures other insulating materials are coming into use. In order to realize the full temperature possibilities of nickel-chromium alloy resistors, moulded-block supports are used, permitting radiation direct from the resistor material.

Terminal requirements for temperatures higher than for water heating are quite different from requirements for electrical terminals at low temperatures. Copper may oxidize, and if brass is used, the zinc may volatilize. Therefore steel is largely used for terminal parts and for bus bars, as in spanning ovens.

32. Methods of regulating heat. Regulation of watt consumption may be required (1) to heat up rapidly from room temperature to operating temperature; i.e., to supply the heat of absorption and latent heat; or (2) to provide for changes in operating temperature; or (3) to provide for operation at uniform temperature where the heat requirements vary during operation. Such regulation may be accomplished as follows: (1) By changing the line voltage impressed upon the heater (see Fig. 4). The watts will vary approximately as the square of the voltage; (2) by dividing the heater into sections, and changing the voltage impressed on each section by connecting the sections in different combinations; (3) by dividing the heater into sections each designed for line voltage, and providing each section with a switch; (4) by the use of a series rheostat, which gives closer regulation than methods (1) and (3) and does not complicate the heater by sectionalizing it; rheostatic control is particularly well suited to heaters with small watt rates; (5) by using a resistor having a high temperature-coefficient of resistance, the increased resistance at higher temperatures reducing the watt consumption automatically and exerting a steadying influence on the temperature; (6) by connecting the heater intermittently to the line, opening the circuit when the maximum operating temperature is reached, and closing the circuit when minimum operating temperature is reached, which is the method generally employed in automatic temperature control; a thermostat or other temperature-responsive device is used and for low watt rates opens and closes the circuit directly, or for higher watt rates actuates a suitable magnet switch; (7) by a time switch for connecting and disconnecting the heater at pre-determined times.

33. Heater ratings. The correct heater rating for any given case is determined by: (1) The best temperature for the process, or service rating;

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) the temperature limits imposed by possibility of contact with inflam-able materials, or of burning operators; (3) the safe life temperature of the ıater, or life rating. Heaters employing nickel-chromium resistors and ica insulation in metal casings are typical of the structures used for most dustrial electric heating applications below red heat or about 1,000 deg. hr. The following energy density ratings in watts per square inch of fective heater surface have been successfully used. These ratings are in-cative of the maximum permissible life ratings, assuming correct heater sign and correct application to the work. Considerations (1) and (2) ›ove may require lower operating temperatures and lower ratings.

Application	Conditions	Maximum rating in watts per sq. in. of effective heater area
Room heating.....	Heaters in free air with good ventilation.	12 to 18 watts per sq. in., *both* sides
Low temperature ovens, such as plate warmers and drying ovens.	Heaters in bottom, good air circulation	10 to 16 watts per sq. in., *both* sides
High temperature ovens such as japanning ovens, core baking ovens	Heaters in bottom, good air circulation	8 to 12 watts per sq. in., *both* sides
Water heating.....	Immersion type heaters, surface of heater free from scale	20 to 40 watts per sq. in., *both* sides
Oil heating.....	Immersion type heaters, surface of heater clean	7 to 15 watts per sq. in., *both* sides
Wax, asphaltum, etc.	Immersion heaters, surface of heater clean	5 to 10 watts per sq. in., *both* sides
Type metals.....	Immersion heaters, surface of heater clean	5 to 10 watts per sq. in., *both* sides
Machine applications	Clean, flat surface of water container with well-fitted heater.....	20 to 30 watts per sq. in., *one* side
Machine applications	Clean, machined surface, casting or other good diffusing body, at 350 deg. fahr.	15 to 24 watts per sq. in., *one* side
Machine applications	Clean, machined surface, casting or other good heat diffusing body, at 500 deg. fahr.	10 to 15 watts per sq. in., *one* side
Machine applications	Good surface of casting not machined, at 350 deg. fahr.	10 to 15 watts per sq. in., *one* side
Machine applications	Good surface of casting not machined, at 500 deg. fahr.	8 to 12 watts per sq. in., *one* side

34. Room heating. To determine the watts required to maintain a ›m at a constant temperature rise above its surroundings, calculate the st losses at that temperature. Total heat losses are made up of: (1) nduction through exposed walls, which depends upon the construction of › walls and varies widely; (2) conduction through exposed glass; (3) air uired for ventilation; (4) air leakage where in excess of (4). Such cal-ation of heat transmission or losses is the only method for determining › heat requirements accurately. In the absence of complete data, the lowing rules may be used. They apply with fair accuracy to average ıditions but will not apply to extreme conditions of size, construction, nperature rise, or exposure.

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Adaptation of Mills rule, 70
Allow 0.35 watts per cu. ft. of
Allow 3.5 watts per sq. ft. of
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air changes per hr., ar

35. Watts required per s
ing examples:
Homes, interior rooms,
Homes, exterior rooms,
Homes, exterior rooms
watts per cu. ft.
Small, isolated, expose
Crane cabs, etc., sheet
Valve houses, etc. 5
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* See

Adaptation of Mills rule, 70 deg. fahr. rise, average conditions*
Allow 0.35 watts per cu. ft. of air.
Allow 3.5 watts per sq. ft. of exposed wall.
Allow 35.0 watts per sq. ft. of exposed glass.

Adaptation of Thompson rule, 70 deg. fahr. rise, average house*
Allow 7.0 watts per sq. ft. of exposed wall.
Allow 35.0 watts per sq. ft. of exposed glass.

Adaptation of Barker rule, 70 deg. fahr. rise
Allow 21.0 watts per sq. ft. of exposed glass.
Allow 5.0 watts per sq. ft. of exposed wall.
Allow 7.0 watts per sq. ft. of exposed ceiling.
Allow 2.0 watts per sq. ft. of exposed floor.
Allow 0.38 watts per cu. ft. of volume, for one air change per hr.; 1 to 3 air changes per hr., are generally provided for.

35. Watts required per cu. ft. of room volume are given in the follow- g examples:

Homes, interior rooms, 0.75 to 1.25 watts per cu. ft.
Homes, exterior rooms, 1.25 to 1.75 watts per cu. ft.
Homes, exterior rooms, with extra glass or greater exposure 1.75 to 3.0 watts per cu. ft.
Small, isolated, exposed rooms 2.5 to 5 watts per cu. ft.
Crane cabs, etc., sheet metal walls, 5 to 15 watts per cu. ft.
Valve houses, etc. 5 to 10 watts per cu. ft.
Street railway cars, 250 to 350 watts per ft. of car length with heaters on "high," the lower figures for city cars, the higher figures for small cars and high-speed interurban lines.

'here a steam or hot-water system is in use or heating requirements have een figured on either basis, assume that 70 watts are equivalent to 1 sq. ft. low-pressure steam radiation (at 240 B.t.u. per sq. ft.) or that 44 watts e equivalent to 1 sq. ft. of hot-water radiation (at 150 B.t.u. per sq. ft.). o heat 1 cu. ft. of air 1 deg. fahr. requires 0.0054 watt-hours, or 0.38 watt heat a supply of 1 cu. ft. of air per hour, from zero to 70 deg. fahr. The ult human body gives off heat at a rate of 100 to 150 watts. This factor of importance in reducing considerably the heat requirements in some cases, in car heating.

36. Household ranges. The following data on typical range loads, mpiled by the Society for Electric Development, are based on reports om 100 representative Central Stations (from the "Electric Range Hand- ook," 1919).

Communities served	1,802
Population	11,760,489
Residence customers	1,101,275
Number of ranges	26,180
Kw. load	118,182
Kw. load, per range	4.75
Average demand per range	2.25
Kw-hr. per range, per annum	1,496
Kw-hr. per day	4.2
Kw-hr. per day per person (based on average of 4.2 persons in average family)	1.0
Effective rate in cents	3.25
79 central stations meet artificial gas at average rate, per 1,000 cu. ft. of	$1.19
21 central stations meet natural gas at average rate, per 1,000 cu. ft., of	0.375

he diversity factor goes as low as 10 per cent. for large installations; e., for 1,000 ranges the total demand is only 10 per cent. of the sum of the dividual range demands. Tests made show an efficiency of 85 per cent. or the electric range, 15 to 20 per cent. for gas ranges and 2 per cent. for oal ranges. Shrinkage of meat is considerably reduced in the electric ven; the average shrinkage, in coal or gas ovens, is 25 to 35 per cent., in he electric oven 11 to 18 per cent. Ranges can be operated more economic- lly if other means are provided for heating water required for boiling, stew- ng, etc. Use of the electric range is closely related to heating of water for ooking and for general purposes.

* See "Heat Transmission," by C. B. Thompson.

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37. Data on Heating Processes and Electric Heating Apparatus

Process	Approximate temperature (deg. fahr.)	Apparatus	Approximate capacity (c) Connected* (a) Average	
Heating valve houses	36– 79	Space or room heaters	200– 300 watts	(c)
Chocolate dipping	98	Chocolate warmers	50– 100 watts	(a)
			2,000 watts	(c)
Bon Bon dipping	136– 156	Bon Bon kettle	500 watts	(a)
Drying photographic films	90– 110	Clothes dryer	60– 90 watts per cu. ft.	(c)
Drying textiles and lumber	120– 200	Plate warmer	100–150 watts per cu. ft.	(c)
Drying, miscellaneous	100– 300			
Glue	130– 150	Glue pots, dry type, 2 qts	320 watts	
		Glue pots, dry type, 3–8 qts	100– 125 watts per qt.	
		Glue pots, water bath, 2 qts	500– 660 watts	(c)
		Glue pots, water bath, 3–8 qts	200– 250 watts per qt.	(c)
		Glue cookers, 3–25 gal	300– 400 watts per gal.	(c)
Celluloid	150	Hot-water tanks, 30 gal	2,000– 5,000 watts	(c)
Melting paraffine	150	Hot-water tanks, 30 gal.; heater on continuously	600– 1,000 watts	
		Fireless cookers	600– 1,500 watts	
Steam generator, 15 lb	250			
Steam generator, 100 lb	340			
Melting waxes and compounds	150– 500	Water stills	2,000– 2,500 watts per gal. per hr.	(c)
Paper embossing	350	Sealing wax pot, ½ pt.–2 qt	175– 300 watts	(c)
Baking Elec. Insul. Material	200– 500	Press heads and blocks	6– 10 watts per sq. in.	(c)
Vulcanising	300	Matrix press	12,000–30,000 watts	(c)
		Stove tops	20– 30 watts per sq. in.	(c)
		Rectangular hot plates	12– 19 watts per sq. in.	(c)
Baking japan and enamel, white	100– 160	Japanning ovens:		
Baking japan, light colors	100– 250	Hand-loaded, best conditions	125– 165	Watt-hours per pound of product
Baking japan, dark colors	300	Truck loaded	85– 100	
Baking japan, black	600	Semi-continuous conveyor	85– 100	
		Continuous conveyor	30– 40	

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Making varnishes	500			
Baking foundry cores	350– 500			
Baking bread	400– 450	Bake ovens:		
Baking rolls and biscuit	400– 500	Small (household)	1,000– 2,500 watts	(c)
Baking cakes and pastry	300– 400	Medium	2,500– 4,000 watts	(c)
		Large (commercial)	425– 750 watts per cu. ft.	(c)
		Large (commercial) shelf area	325– 600 watts per sq. ft.	(c)
Ironing textiles	250– 450	Household iron, 6 lb	500– 600 watts	(c)
		Industrial irons, to 25 lb	to 1,000 watts	(c)
		Ironing machines:		
		Hot roll type	6– 10 watts per sq. in.	(c)
		Hot shoe type	6– 12 watts per sq. in.	(c)
		Soldering irons:		
		Light, to 1 lb	85– 135 watts	(c)
		Medium, to 1½ lb	175 watts	(c)
		Heavy, to 4 lb	500 watts	(c)
Melting tin	450– 500	Soft metal pots:		
Melting lead	620– 700	Small, to 25 lb	450– 800 watts	(c)
		Small, 20–150 lb	600– 2,100 watts	(c)
Melting solder	350– 600	Linotype pot	1,500 watts	(c)
			500– 750 watts	(a)
Melting type metal	550– 850	Monotype pot	2,500 watts	(c)
			1,100– 2,000 watts	(a)
Melting babbitt	450– 700	Babbitt pots, 10 to 150 lb	450– 2,100 watts	(c)
Heating soft-metal moulds	200–1,000			
Annealing copper	350– 700			
Annealing aluminum	500– 800			
Annealing glass	800–1,000			
Tempering steel	200–1,000	Oil tempering bath, 10–40 gal	3,000–30,000 watts	(c)
Sherardizing	650– 700			
Visible red heat in darkness	800– ...			
Visible red heat in daylight	...–1,100			

* Where multiple heat or automatic control is used the average consumption will be lower, usually from ¼ to ½ of the values given for connected watt capacity

38. Household water heating. The average use of water is from 20 to 125 gallons per family per day; temperature 104 deg. fahr. for bath purposes, 150 deg. fahr. for dish washing. If water is heated as required for use, a large demand (2 to 5 kw.) is created for a short time, and under usual conditions does not secure a sufficiently low energy rate to be economical. The rate can be lowered by using a lower demand (0.5 to 1.0 kw.) over a longer time or continuously, *i.e.*, heating the water in advance and storing it in a suitable heat-insulated tank. The demand can also be lowered by arranging a double-throw switch to permit use of either range or water heater, but not both at same time. Effective heat insulation on the tank, to reduce heat loss into the room, is required where water is stored. Automatic temperature control aids in securing constant temperature of stored water, and automatically adjusts the average current consumption to the existing hot-water requirements.

39. Table Showing Efficiency and Gallons per 24 Hours of Water Heated to 104 Deg. Fahr.

(36-gal. tank covered with 1-in. hair-felt insulation on tank and 1-in. magnesia covering circulation piping. Cold water, 39 deg. fahr. Faucet close to tank.)

(Electric Range Handbook, p. 185.)

Kind of system	Kind of equipment	Watts	Efficiency, per cent.	No. gal. hot water available (at 104 deg. fahr.) per 24 hours
Storage.....	Outside circulation	600	82	75
Storage.....	Outside circulation	1,000	76	117
Storage.....	"Clamp-on".....	750	78	89
Intermittent....	Outside circulation	3,000	73	330
Intermittent....	Outside circulation	5,000	69	525

ELECTRIC WELDING

BY OTIS ALLEN KENYON

Engineer, Ray D. Lethbridge, Inc., Member, American Institute of Electrical Engineers, Member Society Automotive Engineers

40. There are three distinct processes of electric welding. (a) the incandescent process; (b) the carbon arc process; (c) the metallic arc process.

THOMPSON PROCESS

41. The incandescent process (known as the Thompson process) is primarily suited for manufacturing operations where more or less standard welds are made. The principle of this process consists in connecting the joint to be welded in a low-potential alternating-current circuit and applying a definite mechanical pressure to the joint while the metal is at the welding temperature. The heating energy may be taken from any alternating-current system. The welding machine itself consists of suitable clamps for holding the pieces to be joined, and a means of applying pressure. The clamps, together with the joint, close the secondary circuit of a transformer, and these terminals are usually water cooled. Fig. 5 gives the average power and time required to make welds of iron and steel by the incandescent process. It may be noted that the power in kilowatts and the time in seconds are numerically equal. Herman Lemp states that the energy required to bring iron to the welding temperature is approximately 7 h.p.-min. per cu. in. of metal.

42. Temperature distribution. In making incandescent welds it is important that the temperature distribution over the face of the joint should be as uniform as possible. Alternating current assists in meeting these requirements as, on account of skin effect, the current density is greater near the surface than at the center, which tends to maintain an even temperature

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throughout the joint in spite of the radiation from the surface. On account of the necessity for uniform temperature distribution, it is impracticable to butt weld two pieces of different areas, as the smaller one will become much hotter than the large one. For this same reason it is also impractical to butt-weld large surfaces, as the current will not distribute itself uniformly over the section.

43. Spot welding. To overcome the difficulties due to non-uniform temperature distribution, what is known as spot welding has been developed. In spot welding the best results are obtained by punching the surfaces to be

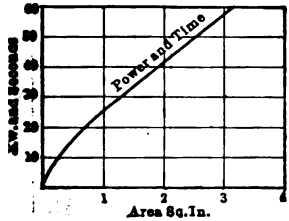


FIG. 5.—Power and time required to butt-weld iron rod by incandescent process.

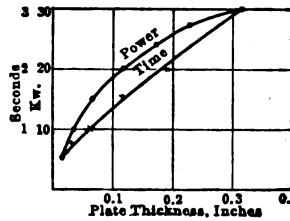


FIG. 6.—Power and time required to spot-weld steel plate by incandescent process.

welded in such a way that a series of joints of equal and definite area are made between the two. Fig. 6 gives the average power and time required to make welds by the spot-weld process. Fig. 7 shows how a disc may be welded to a surface by this process; also how two flat surfaces may be welded together. The whole object of the spot-weld process is to reduce the welded joint to an area of definite and uniform dimensions.

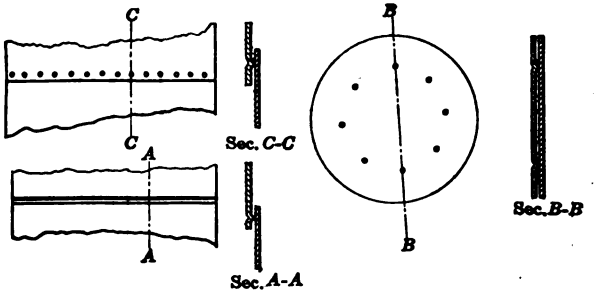


FIG. 7.—Spot welds.

A modification of the spot-weld principle is shown in the lower left-hand corner of Fig. 7 where instead of a series of spots we have a V-shaped depression in one of the plates which makes an edge contact with the plate to which it is welded. The current is then passed through the plate by means of a wheel which runs in the grove and exerts the necessary pressure for welding. The ordinary spot welder used extensively in sheet-metal work relies entirely on the pressure between the contact points to confine the current to a definite area.

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44. Power and Energy Absorbed in Electric Welding.—Professor Thomson's Process

Iron and steel					Brass					Copper				
Area sq. in.	Watts in primary of welders	Time sec.	H.p. applied to generator	Kilo ft.-lb.	Area sq. in.	Watts in primary of welder	Time sec.	H.p. applied to generator	Kilo ft.-lb.	Area sq. in.	Watts in primary of welders	Time sec.	H.p. applied to generator	Kilo ft.-lb.
0.5	8,550	33	14.4	260	0.25	7,500	17	12.6	117	0.125	6,000	8	10.0	44
1.0	16,700	45	28.0	692	0.50	13,500	22	22.6	281	0.25	14,000	11	23.4	142
1.5	23,500	55	39.4	1,191	0.75	19,000	29	31.8	508	0.375	19,000	13	31.8	227
2.0	29,000	65	48.6	1,738	1.00	25,000	33	42.0	760	0.500	25,000	16	42.0	369
2.5	34,000	70	57.0	2,194	1.25	31,000	38	52.0	1087	0.625	31,000	18	51.9	513
3.0	39,000	78	65.4	2,804	1.50	36,000	42	60.3	1390	0.75	36,500	21	61.2	706
3.5	44,000	85	73.7	3,447	1.75	40,000	45	67.0	1659	0.875	43,000	22	72.9	872
4.0	50,000	90	83.8	4,148	2.00	44,000	48	73.7	1947	1.000	49,000	23	82.1	1,039

NOTE.—The stock should be clamped in the machine so as to fulfil the following relations: Iron and steel: $l = 2d$; brass: $l = 3d$; copper: $l = 4d$, wherein l is the distance between the inside face of the clamps and d the diameter of the stock to be welded.

CARBON-ARC PROCESS

45. Characteristics of Carbon Welding Arc

(C. B. Auel, Amer., Mach., Mar. 16, 1911)

Arc length. (in.)	E.m.f. across arc and carbon (volts)	Current (amp.)	Length carbon (in.)
6	101	300	1×6.5
5	98	350	
4	93	400	
3	86	605	
2	80	750	

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46. The carbon-arc (Bernardos) process has been in use about 25 years. In this process the heat of the arc is utilized to bring the metals to be joined to the welding temperature, and a melt bar of the same material as the parts to be joined is introduced in the joint to fill the space between the pieces. In welding with a carbon arc, the parts to be joined are connected to the positive side of the circuit, and the carbon electrode to the negative side. A direct-current generator of from 80 to 125 volts is generally used. The current capacity varies with the nature of the work from 15 to 600 amperes. The lowest values are used on sheet-metal work, and with non-ferrous metals; the highest values are used on massive castings. The carbon arc, except for low-current values, is long and behaves very much like a flame, therefore, it is necessary to manipulate it like a flame by giving it a circular motion, such as is done with the oxyacetylene flame.

47. Application. The carbon-arc process is suited to work where either very large or very small amounts of energy are to be developed, such as filling holes in castings and melting large masses of metal or welding thin metals or facing non-ferrous metals. As disadvantages the following may be mentioned: the likelihood of carbonisation of the weld with consequent porousness of the metal; the large area which is heated by the arc; the necessity for using both hands on high-power arcs.

48. Stresses due to temperature changes. On account of the large area which is heated by the arc flame, it is necessary to exercise extreme care in order to avoid stresses and distortion due to temperature changes. Therefore, in many cases it is necessary to preheat with a gas flame the objects to be welded.

49. Protection of operator. The light and radiated heat of the arc are so intense that the skin and eyes must be protected. Therefore, since both hands are required to do the welding, it is necessary to provide the operator with a helmet; this helmet prevents him from examining the work carefully as it progresses.

50. The carbon arc may be used for cutting steel, such as sheet piling and structural steel of buildings, bridges, etc., which have to be cleared away. It can also be used for cutting cast iron. The speed of cutting depends on the current; for thicknesses above ½ in. the current should not be less than 200 amp.

METALLIC ARC PROCESS

51. Process. To Slawianoff is given the credit for inventing the metallic arc process wherein the filler rod itself is made an electrode and fused into the joint by the arc between it and the surface of the joint. The metallic arc is shorter and less stable than the carbon arc, and therefore requires better control of the electric current for good results than the carbon arc process.

52. The arc e.m.f. varies from 18 to 24 volts but can be taken as 20 volts for the purpose of calculation. Tests indicate that the e.m.f. of the arc does not vary with the current through the arc but only with the length of the vapor stream. With automatic electrode feeding, successful welding has been done with a 12-volt arc. Therefore, it may be assumed that any e.m.f. above this is not necessary for welding, but serves simply to increase the flexibility of the arc and thus aid the operator in holding the arc. The longer the arc the greater the superheating of the metal, and the greater the exposure to the atmosphere. Therefore, under all conditions the arc should be as short as the operator can hold. If the arc is held too short, it ceases to be an arc and becomes a series of discharges. It is easy to tell by the sound whether an arc is too short or too long. It crackles and spits when it is too short, and when it is too long it fluctuates violently. When it is just right it makes a smooth sound.

53. The arc current should be chosen to conform to the type of joint and the size of electrode. *Open joints* where the entire surface is easily accessible to the arc, can be successfully welded with the wide range of current. If the joint is deep or narrow, or otherwise inaccessible to the arc, it is necessary to use a current large enough in value to fuse through the joint at all points.

54. The effect of electrode size on the current is independent of the joint. The rate of melting is determined by the arc current. Therefore,

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the higher the current the faster the melting of the electrode. It is desirable to use as high current as the welder can handle. A rough guide for current as related to electrode diameter is given in Par. **55.**

55. Current range for soft steel electrodes.

Hand welding			
Diameter, inches	Amperes		
	Low	High	Fusing
0.062	20	40	50
0.094	40	65	90
0.125	105	115	140
0.135	120	130	160
0.156	140	160	200
0.188	190	210	260

56. Electrodes have received a great deal of study but little real progress has been made when judged on the basis of results in welding. It has not yet been proven that there is anything better than the bare soft steel electrode. **Coated electrodes** permit the use of inferior metal and improve the stability of the arc, but they are not necessary to the highest quality of welding. Good electrodes must be mechanically perfect; that is, free from included slag, pipes and slivers.

57. Joints. As far as *joints* are concerned, the surfaces of the parts to be joined should always be so disposed as to facilitate to a maximum degree the playing of the arc on all parts, and yet the design should be such as to avoid unnecessary volume of metal in the weld. Where possible, the joint should be backed up with metal to increase the heat conductance, and permit the use of high currents.

58. In manipulating the arc the electrode should be pointed slightly toward the completed weld, and the arc played in such a way as to advance the crater first along one edge of the joint, then pass the arc back and across the weld and advance along the other edge and so on, executing a series of crescents and keeping the metal always along the trailing side of the crater. If the arc is broken and the crater is not on the very tip of the weld, trouble will be experienced in starting the weld again, in such a way as to make a sound joint between the old crater and the new metal.

59. In production work where more or less unskilled labor must be employed, it is desirable to fix as many factors in the welding process as possible. First of all, the joint should be maintained within definite limits, next the current should be set at a predetermined value depending upon the joint and the size of electrode. The size of the electrode depends in this class of work largely upon the result desired. Small electrodes require slower work on the one hand; while on the other hand they force the operator to cover thoroughly with the arc the surfaces to be welded, and thus produce a high-quality weld. Large electrodes permit faster work—they also make it easy for the operator to execute poor welds by allowing metal to flow into the joint outside of the arc crater. However, large electrodes and high currents do not necessarily mean poor welding. It simply means that the job is more dependent on the operator under such conditions.

60. Electric energy for welding may be supplied from any suitable source, both alternating current and direct current being in use at the present time. If a constant-potential generator is used, some provision must be made for stabilising the arc circuit. Usually, this involves a ballast resistor which absorbs at least two-thirds of the energy supplied by the generator. When a fixed resistor is used 80-volts on the generator gives the best all-around results. Several different types of differential machines are used for arc welding service. These are all single-arc machines and all use a reactor in series with the arc to stabilize the current fluctuations. The alternating-current welding transformers have a characteristic similar to the differential machines; that is, the e.m.f. falls with rising current.

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61. Closed-circuit series system of supply. For production work the closed-circuit series system which was used on the liberty engine cylinders has advantages over the single-arc systems, in that it permits the use of larger machines without the sacrifice of individual control of the various arcs. In this system the generator produces a constant-current, and controllers are connected in series in the line, each controller serving one arc. The purpose of the controller is to maintain the continuity of the line and to limit the e.m.f. across the arc, and to control the arc leads. It is possible to predetermine and fix the current, and the arc e.m.f., and maintain the proper welding values independently of the operator.

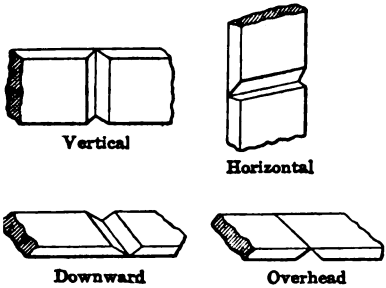


FIG. 8.—Conventional arc-welding positions.

62. The cost of metallic-arc welding includes the following factors: welding electrodes, fluxes (when used), labor, energy and fixed charges. In general it may be said that the electrodes and fluxes should be about the same in a given case as the corresponding expense for the carbon-arc, and the oxy-acetylene processes. In all three cases the labor is skilled, and is paid at about the same rate. Therefore, the labor

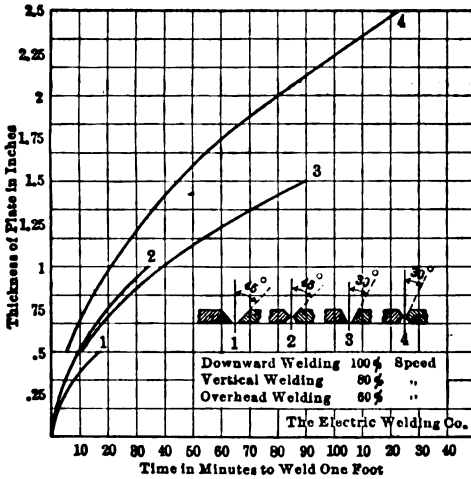


FIG. 9.—Time required to weld seams of various thicknesses by metallic-arc process.

cost of welding depends on the speed (see Fig. 9). For thin plates, the oxy-acetylene process is faster than the electric arc. However, for sizes above 0.125 in. the arc is faster, therefore the labor item is less. The cost

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of energy depends on local conditions and can be accurately calculated for any given case from the data here given. In comparing arc-welding costs with oxy-acetylene-welding costs, the cost of electric energy is balanced against that of oxygen and acetylene.

63. Advantages. The extreme localization of heat in the metallic-arc process is an enormous advantage, especially where large masses of metal are concerned, as it minimizes stresses due to expansion and contraction with the practical result that preheating need not be resorted to nor must the joints be more open at one end than at the other to allow for expansion, as is the case with hot-flame and carbon-arc processes. Another advantage of the metallic arc is that the operator uses only one hand for welding, leaving the other free to manipulate a glass screen. This he holds before his face when the arc is on, and lowers each time the arc breaks in order that he may examine the work and closely control its quality.

64. Strength of weld. Experience shows that with a metallic arc, welds can be made in which the strength of the joint is the same as that of the metal itself and even greater. However, on account of inferior work that has been done by unskilled welders, engineers are inclined to avoid arc welding except in cases where it can be subjected to test before putting it into service. If some method of inspection could be developed whereby the quality of a finished joint could be determined without damaging it, welding would undoubtedly displace riveting in a great many structures, and thus an enormous saving in labor and materials be accomplished.

65. Porosity test. Wherever the character of a joint is suitable, its porousness may be tested by applying kerosene to one side. Kerosene will penetrate a porous joint that is so tight that water under high pressure could not penetrate it. In this way the soundness of welds may be tested and a really unsound weld will reveal itself under a few minutes' application of kerosene.

66. Literature. The May, 1913, *Bulletin* of the New York Public Library gives a list of works relating to electric welding, covering the period between 1786 and 1912, inclusive, comprising several hundred articles and books in English and foreign languages, as well as references to the most important patents.

ELECTRICAL EQUIPMENT FOR GAS AUTOMOBILES

BY JOHN C. BOGLE

Engineer, Cook Electric Co.; Associate, Amer. Inst. Elec. Engineers

BATTERIES

70. Type adaptable to requirements. It is standard practice to employ the pasted-plate lead cell for gas-car service. The advantageous features of this type of cell are: economy of space and reduction of weight together with a low internal resistance. The cardinal feature of the pasted-plate cell is a high short-time amperage. The requirements of electric cranking positively demand the pasted-plate type as the only practical cell for the purpose.

The battery should be of rigid construction, capable of withstanding the severe vibration to which it will be subjected in service. Jars are constructed of hard rubber having relatively high tensile strength and some flexibility.

Separators of wood or hard rubber are usually inserted between adjacent plates; these should be perforated or otherwise so constructed that they will interpose no appreciable increase in internal resistance.

71. Methods employed in charging. On pleasure cars, where the storage battery has almost universal application, the charging is done from a generator driven by the gas motor. Charging on removal from the car must be attended with precautions observed with any battery (see Sec. 20). In addition, however, separate precautions should be taken in case the battery is to be left out of service for any considerable length of time. Under these conditions it should receive attention and charge at least once a month. When the battery is to be put back into service it should first receive an overcharge for several hours at the normal rate.

72. Freezing. Care should be taken in cold weather to prevent the electrolyte from freezing. Following is a table of freezing temperatures (deg. fahr.) corresponding to various specific gravities. For reduction of battery capacity with decreasing temperatures, see Sec. 20.

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Specific gravity	Condition	Temperature
1,290 deg.	Fully charged.....	− 100 deg.
1,260 deg.	¾ charged.....	− 60 deg.
1,225 deg.	½ charged.....	− 38 deg.
1,160 deg.	¼ charged.....	0 deg.
1,125 deg.	Completely discharged..	+ 13 deg.

73. Ampere-hour capacity. Examples of capacities common with 6-volt systems may be cited; these battery sizes range from 80 to 160-amp-hr., figured on a 10-amp. discharge rate, and the majority of installations range from 100 to 120 amp-hr. capacity. Such batteries are sufficient for electric cranking and for car lighting when not running.

74. Battery discharge rate during cranking. From the curve of Fig. 10,* it will be seen that if a battery is discharged at the 20-min. rate, an amp-hr. capacity will be realised with an approximate value only 30 per cent. of that obtained at the normal 8-hr. discharge rate. This means that a battery with a normal rating of 120 amp-hr. will furnish only 36 amp-hr. if allowed to discharge completely in 20 min., and the current will be in the neighborhood of 110 amp. if maintained uniform throughout this period. Compare this figure with the result of a test, shown in Par. 78.

75. Location in car. The most desirable location, in point of accessibility, is upon the running board. Accessibility is highly important; otherwise, it is extremely doubtful whether the battery will receive proper attention.

ELECTRIC STARTERS

76. Process of electric cranking. The starting of gas-car engines by electric motors, depends for its success upon the possibilities of obtaining enormous current discharges from storage batteries, these discharges necessarily extending over as short a time as possible. When the battery current is applied, the electric motor rotates the crank shaft, thus driving gas into the cylinder, in turn compressing the gas, and finally exploding it.

At present, cranking speeds average 100 rev. per min. and higher. Such speeds are, of course, not realised if, under operating conditions, the battery voltage is low.

77. The cranking current depends upon the engine dimensions, the degree of compression, the number of cylinders, the friction, and upon certain exigencies such, for example, as obstruction in any part of the starting mechanism. The cranking current with 6-volt systems will usually be about 80 amp. for the lighter cars, and will not greatly exceed 140 amp. for the heaviest. The proper value of cranking current can only be determined accurately as the result of exhaustive tests, which take into consideration all possible rigors to which the equipment may be subjected in service.

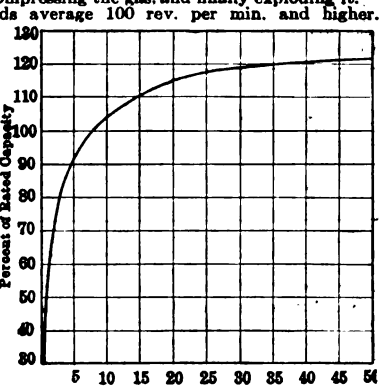


FIG. 10.—Variation of amp-hr. capacity with different discharge rates.

78. Typical starting-test data.† Commercial starter turning dead engine. A 6-volt, 120-amp-hr. (on 10-amp. discharge rate) battery was

* *The Automobile*, Feb. 6, 1913; page 421.
† Vesta Accumulator Co., April, 1914.

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used. Car had been run about 2,000 miles, and engine was warm at time of test.

Time	Volts per cell	Cranking current	Rev. per min.	Specific gravity
3:00 P.M.	2.00	95	120	1300
3:05 P.M.	1.99	91	116	1295
3:10 P.M.	1.96	95	116	1280
3:15 P.M.	1.93	97	116	1280
3:20 P.M.	1.88	102	112	1275
3:25 P.M.	1.84	103	112	1270
3:30 P.M.	1.80	105	112	1265
3:35 P.M.	1.72	110	112	1255
3:38 P.M.	1.52	110	100	1250
3:39 P.M	Stopped			

79. The momentary discharge rate at the instant of starting is dependent on the **breakaway torque** of the engine, which consists chiefly of static friction and inertia. This current surge seldom exceeds from three to four times the cranking current measured after the motor has attained full cranking speed (Par. 78) except where sleeve-type engines are being started. In the latter case the momentary discharge will possibly be at a rate of eight times the operating cranking current. Momentary discharge rate is usually not the determining factor in the choice of battery capacity when all things are considered.

80. Duration of the cranking period. The length of time required for starting is a function of the efficiency of carburation, the engine cranking speed, the number of cylinders, and the general good repair of the car. The following test was made in February, 1914, by the Royal Automobile Club, London, on a commercial starter operating at 24 volts.

The device was submitted for the test fitted to a 20-h.p. Ford car. The dimensions of the engine were 95 mm. × 102 mm. The volume swept by the piston was 723 cu. cm., and the cubical contents of the compression space was 209 cu. cm. The engine of the car was started, on six consecutive days, two hundred and fifty times per day.

Day	No. of starts	Total time taken for starts
1	250	13 min. 18 sec.
2	250	11 min. 22 sec.
3	250	13 min. 32 sec.
4	250	11 min. 41 sec.
5	250	11 min. 37 sec.
6	250	11 min. 3 sec.

The engine was switched off and was not run between starts. The first start each day (cold) took somewhat longer (a maximum of 14.4 sec.) than the others, which were practically instantaneous. At the close of every day the car was run for half an hour to charge the battery.

81. Single-unit and two-unit starters. Where the generator used for charging the battery is combined with the cranking motor to form one machine, the resultant arrangement is termed a single-unit system. Where the two functions are divorced the starter is called a two-unit system. The single-unit machine is somewhat erroneously named a "motor-generator" inasmuch as it has most of the characteristics of a series motor when used for starting and most of the characteristics of a shunt generator when it is charging the battery. The motor-generator is at all times in gear with the power plant of the car. The motor of the two-unit system is only in mesh with the power plant during the process of starting. A clutch or drive is interposed between the motor and the power plant. When the gas motor is under its own power, the accelerated speed of the formerly driven member frees the power plant from its starting motor. On the other hand, the generator of the two-unit system always revolves with the engine crank shaft.

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82. An automatic cut-out or relay is provided for applying charging urrent to the battery when the generator speed has reached the charging alue, and for disconnecting the generator from the battery when the speed alls below this value. Automatic cut-outs are usually adjusted to operate t car speeds of from 12 to 15 miles per hr.

The device is simply a reverse-current relay, taking several forms, one eing illustrated in Fig. 11. The potential coil of this relay is connected

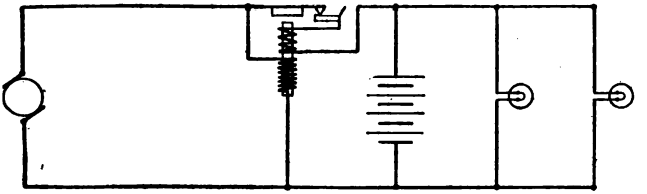


FIG. 11.—Typical automatic cut-out.

ermanently across the generator terminals, and when the generator has eached the predetermined voltage, the coil is sufficiently energized to close he relay contacts. Current then flows through the series winding of the elay to battery, strengthening the pull due to the potential winding. Should he generator slow down below the predetermined charging speed, the gen- rator voltage will fall below the battery voltage and the reversed current n the series winding of the automatic cut-out will deenergize the core and llow the armature to drop away, thereby disconnecting the generator from he battery.

The cut-out is not for the purpose of opening the circuit when the battery s fully charged and the engine still continues to run. Indeed, in the opera- ion of gas cars it will not be necessary to provide equipment for performing his operation, as it will be found almost impossible to charge the battery ontinuously at a high rate, because the car will seldom travel at high speeds or intervals of any appreciable duration.

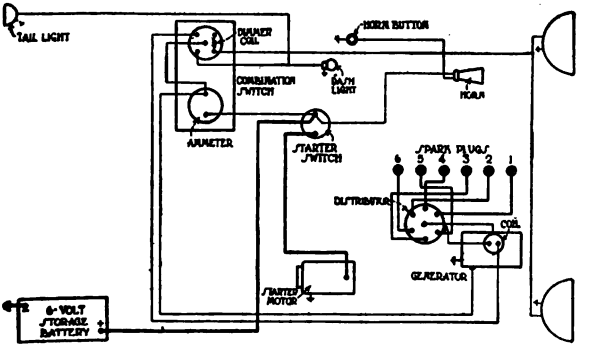


FIG. 12.—Two-unit wiring system.

83. Charging control. Irrespective of the method of starting, whether ingle-unit or two-unit, some provision must be made for limiting the charg- ng currents at high speeds. This provision is distinct from the automatic ut-out, whose function is to connect the generator to the battery when the ngine speed exceeds a fixed value and to disconnect when the engine speed

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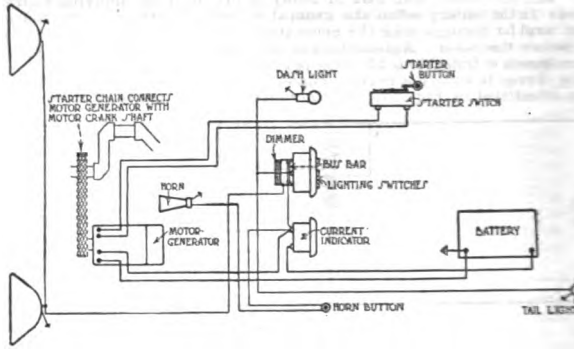


FIG. 13.—Single-unit wiring system.

falls below this value. The charging generator must be so regulated that high speeds the charging rate is kept within proper bounds. It has been found possible to design generators which deliver their maximum output at the predominating speed of car operation, and which will deliver less and less as the car speed is increased. The methods of securing this end are extremely diverse, having been developed by a host of experimenters working independently. Since the application of the starting principle in 1913–1914, the development of these various methods has proceeded until the control systems of today are rugged, positive and trustworthy

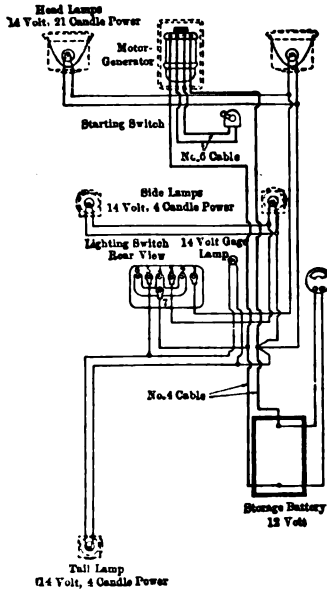


FIG. 14.—Lighting system.

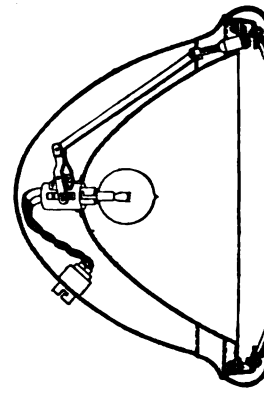


FIG. 15.—Focusing lamp.

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LIGHTING

84. Reflectors are of many shapes, and perform the same function as the backing of any ordinary headlight. It is essential for efficient use that they focus properly, and that the beam have proper alignment with the direction of car motion. Some lamps are provided with a mechanism by which the bulb may be either advanced or retracted until the proper focus is obtained. Proper alignment is secured by focusing the ray to a pencil beam and then aligning the lamp by resetting the props. A focusing lamp is shown in Fig. 15.

85. Wiring for lighting systems must be installed with a view toward permanence of insulation and contact. Oil will depreciate rubber insulation, hence automobile wire is cloth-covered. If a grounded or a one-wire system is used, care must be taken to secure a perfect and lasting ground on the metal frame of the car. Simplicity in the arrangement of leads is essential, for repairs are likely to be made by operators absolutely uninformed regarding the simplest electrical circuits.

Lamps are usually controlled from a multi-point switch located within easy reach of the operator.

86. Candle-power and wattage of automobile lamps. The efficiency of low-voltage tungsten lamps, such as are used in the lighting of gas cars, closely approximates 1 watt per c-p. The following table will show the sizes usually adopted for automobile lighting:

Head lamps	15 to 21 c-p.
Tail lamps	2 to 4 c-p.
Side lamps	6 c-p.

15 watts represent the power-consumption of two side lamps and one tail lamp.

30 watts represent the power consumption of two head lamps and one tail lamp.

45 watts represent the power consumption of two head lamps, two side lamps, and one tail lamp.

60 watts represent the power consumption of two head lamps, two side lamps, one tail lamp, one dome lamp, two pillar lamps, and one gage lamp.

87. Arrangement of lighting units is suggested by the preceding paragraph. See also Figs. 12 ,13 and 14.

IGNITION

88. Processes involved in ignition. Ignition of the mixture in the cylinder should occur in such manner that the combustion of gas takes place when the piston is at the head of its stroke. There is a perceptible lag of time from the commencement of the process of sparking until the charge is completely fired. This interval depends upon the rate of gas combustion, the inductive lag, and also the inertia of the vibrator, if such a device be used. At low engine speeds the travel of the piston during this interval is relatively slight. At higher speeds, however, the effect of this delay is to retard the spark until the piston has completed a considerable portion of its downward travel, and in this case some corrective measure is almost imperative. See Par. **92.**

Proper starting of the process involved in firing the charge necessitates that an electric contact be made and then broken at the exact instant required.

The energy source is either a battery or a magneto. Currents of a few milliamperes are caused to cross an air-gap within the cylinder. One terminal of this air-gap is grounded on the engine. The lead from the other terminal passes through an insulating and gas-tight bushing, called a **spark plug,** to the source of high-tension energy.

The spark points are separated 0.4 or 0.5 mm. The voltages across the gap may very roughly be estimated at about 20,000 volts.

89. Variation of spark. The time interval or lag from the operation of the contact breaker to the complete firing of the charge in the cylinder is practically constant at all speeds. On the other hand, the travel of the piston during this interval is proportionately increased as the speed increases.

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The process of ignition, then, must be commenced at a more advanced position at the higher speeds. If a high-tension magneto system is used, it is desirable that the primary circuit be broken when the current is at its maximum value. The characteristic e.m.f. curve of a magneto, particularly at low speeds, is decidedly pointed, which narrows perceptibly the range of spark variation which may be profitably accomplished. This difficulty, however, may be obviated by rotating the field magnets to correspond with the change in the point of break at the contact breaker. Where battery ignition is used in connection with the single-spark system, a somewhat wider range of spark variation may be realised.

The spark variation may be accomplished manually, or, by means of governing apparatus, the process may be made automatic. This relieves the operator of the care and attention bestowed on the spark lever, and, in addition, accurately determines the proper position of the spark for all engine speeds.

90. Multiple-vibrator system (Ford ignition). Where there are more than one cylinder it is possible, by supplying duplicate ignition units (a separate unit for each cylinder), to secure firing which is approximately synchronous. In Fig. 16 may be seen four separate induction coils, each supplied with its own vibrator. The primary circuit of each one of these coils is completed by a contact maker, which at the proper time (here indicated by the position of a cam), closes the primary circuit of the coil corresponding to the cylinder which is to be fired, and, by the action of a vibrator, causes a spark in that cylinder. Synchronised ignition for four or more cylinders with this method, can be only approximate at best. It is impossible so to attune the vibrators that they will respond equally to the action of the timer. The time lag, mentioned in Par. **91**, may vary for each of the several cylinder equipments. The effect of this is improperly timed firing, and the smoothness and economy of the engine as a whole is greatly reduced. It is due to these difficulties that multiple-vibrator ignition is losing in favor, and at present appears on only one make of car, where it is employed solely in the interest of economy.

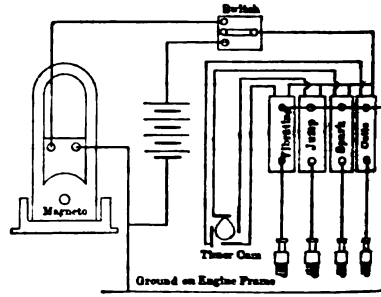


FIG. 16.—Multiple-vibrator system.

91. Magneto and battery ignition. Prior to the universal adoption of electric starting and lighting systems, the magneto was decidedly in public favor. Except for a scattering of cars equipped with storage battery ignition, alternative recourse was had only to dry cells as a source of energy. With the later developments in the starting-lighting field it was found possible to secure single-spark ignition from a battery and a coil, similar to the single-spark ignition derived from a magneto. In the interest of simplicity there has been a great movement away from magneto ignition for pleasure cars to battery ignition. On trucks, however, the magneto has many decided advantages. Comparatively few trucks are equipped with electric starters, hence the storage-battery is not essential and the magneto is used by virtue of its dependability.

Single-spark battery ignition greatly resembles magneto ignition. Each system includes a distributor, which is a single-pole multi-point switch for applying a high-potential discharge to each spark plug in turn. Each has a mutual induction coil whose primary is opened and closed by a switch driven from the crankshaft.

92. High-tension magneto. In the high-tension magneto the distributor and breaker switch are geared to the same mechanism. The double

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coil is a part of the frame of the magneto, either stationary in the inductor type or mounted on the rotor in the revolving type. The connections are internal and only five wires emerge, these being the high tension leads to the distributor and one for switching the magneto into and out of service.

It has been possible to perfect a magneto which will operate successfully at magneto speeds as low as 60 r.p.m. A late development is the impulse starter, a device for securing momentarily high-magneto speeds with but one pull of the crank, this being done by snapping the magneto past a restraining pawl by means of a spring interposed between the magneto shaft and the driving means. Other improvements have been the selection of unidirectional impulse, from which it is claimed a higher efficiency of ignition is secured.

The operation of the magneto is at short-circuit except during the propagation of impulses, when the circuit is snapped open. This break should be at the top of the wave for best results.

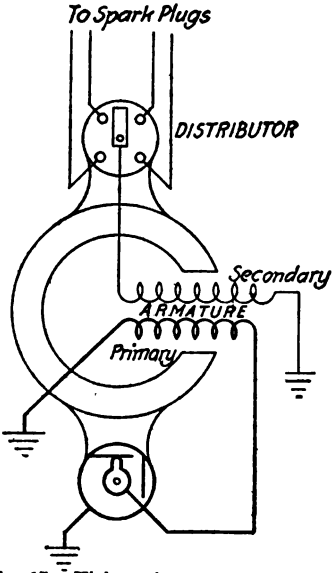


FIG. 17.—High tension magneto with induction coil on armature.

93. Single-spark battery ignition. This form of battery ignition is normally open circuited except just before the impulse is to be sent to the spark plugs. The process of firing is the momentary closure of the circuit and the sudden opening immediately hereafter. Enough time must elapse thoroughly to saturate the magnetic circuit before the circuit is opened. The sudden break induces a kick of high potential in the secondary of the coil, and this discharge is

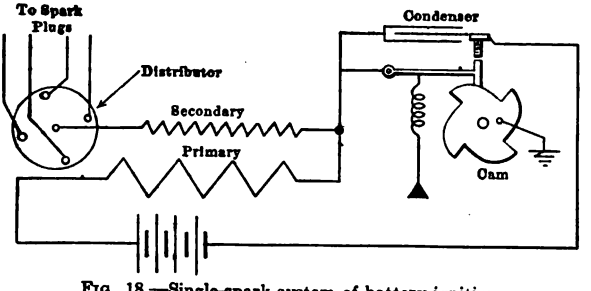


FIG. 18.—Single-spark system of battery ignition.

directed to the proper spark plug by means of the distributor. Such a system is shown in Fig. 18.

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THAWING WATER PIPES

BY H. B. GEAR, A.B., M.E.

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Member, American Institute of Electrical Engineers

94. Advantages of electrical method. The thawing of frozen wate pipes by the use of electrical energy has become quite common in the northern states. During unusually long-continued periods of weather when the tem perature is averaging 10 deg. Fahr. and lower, the frost reaches such a depth in the earth that service pipes and occasionally the smaller water mains be come frozen. Service pipes of less than 2 in. in diameter may be reach thawed by passing electric current through them in sufficient quantity t raise the temperature of the pipe above the freezing point. This permits th water to pass around the central core of ice and if pipes are kept open the flo of water from the main completes the thaw process within a short time after the flow has begu The thawing of water p the use of electric curre is obviously far cheape than by other methods, no excavation is necessa and as very little remai to be done after the flo of water has been estab lished.

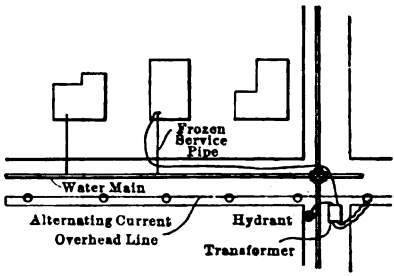


FIG. 19.—Use of transformers for thawing.

95. The methods by which the thawing of pipes have been accomplished are various and involve the use of both direct and alternating cur rents. The use of direct current is permissible only where there is a separate generator of ample capacity available, or a network of capacity sufficient to deliver 500 to 1,000 amp. Where the supply is drawn from a separate generator the control of the flow of current is readily accom plished by the field rheostat. Where the supply is drawn from a low-tension direct-current network the voltage must be reduced by the use of resistance coils. With alternating-current service, it is customary to use a special pipe thawing transformer, having a variable impedance, or a combination of standard transformers so connected as to give the proper voltage and current. The most common pipe-thawing problem is illustrated in Fig. 19, where the service pipe running from the street main to the house is frozen. In order to

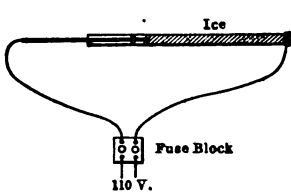


FIG. 20.—Method of thawing by inserted wire.

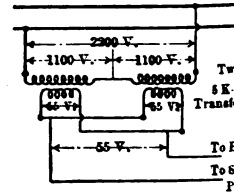


FIG. 21.—Connections for use of standard transformer.

pass current through the service main, the circuit is completed as shown in the illustration from the transformer through the street hydrant, water main and service pipe and back to the source of supply. Where a hydrant is not readily accessible the circuit is sometimes completed through the water piping system of an adjoining building. In connecting to a service pipe

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s desirable to disconnect the house piping in order to prevent stray current rom passing across to gas piping or grounded electric circuits. Fires have een started in some cases where this precaution was not taken and the elec- ric-service companies in many cities require that the water piping be discon- ected from the service before the current is turned on. In cases where he street main becomes frozen, current must be circulated between two djoining hydrants. Such cases, however, are comparatively rare, as freez- ng does not take place in sufficient amount to stop the flow of water.

96. Another method of thawing pipes, using a small amount of energy, s shown in Fig. 20. With this scheme a piece of rubber-covered wire is hrust into the end of the pipe and a current of about 20 amp. slowly melts he ice. A disc of insulating material centres the wire and prevents it from naking contact with the pipe. This method is only applicable where the ipe is straight and where the end is accessible.

97. Power capacity required. In thawing ordinary house services vhich are not over 1½ in. in diameter, it has been found that a transformer apacity of about 30 kw. is ample to start water flowing in from 15 to 30 min. Where standard transformers are used, the connection shown in Fig. 21 has een quite generally employed; this affords about 55 volts and from 350 o 500 amp. Standard transformers may be safely overloaded 50 per cent r more for 15 min. during the cold weather in which this kind of work is done.

The thawing of a 6-in. (15.24 cm.) main, 1,700 ft. (518 m.) in length in the East River at New York required the use of 750 kw. for 36 hr. In this case he pipe was laid in the bed of the river and was surrounded by salt water aving a temperature of about 30 deg. Fahr. It was very difficult to raise the emperature sufficiently to thaw the ice inside, as the heat was carried away o rapidly by the moving water around the pipe. The accompanying table ives data on the amount of current and the length of time required to thaw rozen water pipes by electricity. ("Proceedings of American Water Works Association," 1912. *Eng. and Cont'g*, Feb. 12, 1913.)

Size pipe (iron)*, in.	Length, ft.	Volts	Amperes	Time required to thaw, min.
¾	40	50	300	8
1¼	100	55	135	10
1¼	250	50	400	20
1	250	50	500	20
				Hours
1	700	55	175	5
4	1,300	55	260	3
10	800	62	400	2

* To thaw out lead pipe, the current must be increased 50 per cent.

MARINE APPLICATIONS OF ELECTRICITY

BY H. A. HORNOR, B.A.

'ellow, American Institute of Electrical Engineers, Member, Illuminating Engineer Society, Member, American Electro-chemical Society, American Society of Naval Engineers.

MERCHANT MARINE PRACTICE

98. Rules for installations. In general the electrical construction on ıerchant vessels must comply with the requirements of the classification ɔciety under the rules of which the vessel is constructed. Such societies re established in all the large maritime countries. The American Bureau f Shipping and Lloyd's Register of British and Foreign Shipping are the ɔcieties under which most of the merchant vessels of this country are built. ı addition, the Navigation Laws of the U. S., and the Pilot Rules, issued by ıe Department of Commerce, must be carefully followed. For certain ıland vessels, especially those plying to and from New York City, the ational Board of Fire Underwriters specify and inspect the installation. o cover detail requirements and special operating features the vessel owner so provides a general specification both for use in obtaining a price as well

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as for an instrument of guarantee. These rules and specifications give a wid latitude to the engineer, and in many cases the finished installation more than covers the requirements. This is due to rapid advance in the art.

99. Lighting circuits. The distribution of energy is the same as in a two-wire system on land. Feeders are led from the switchboard to dis tribution cabinets, and branch leads are thence distributed to groups of lamps. Not more than 660 watts are assigned to one branch line. The usual allowable voltage drop to the farthest outlet is 3 per cent.

100. Running lights. In accordance with law, every vessel carries the following navigating lights: (a) masthead; (b) port; (c) starboard; (d) stern; and (e) range. A special feeder is carried to a tell-tale board located in the pilot house, and from this board separate branch lines communicate with each running light. In the event of failure of the lamp in any running lantern, both a visual and an audible signal is indicated by the tell-tale. There are several methods employed to accomplish this purpose, but care in selecting a system need only be exercised as regards ruggedness of construction and the prevention of corrosion.

101. Lighting fixtures. For those places in the vessel subjected to the action of steam or to mechanical injury, and where the outlet would be exposed to the weather, a special water-tight or steam-tight fixture is provided, and frequently a substantial guard is placed over the glass globe. In this country it is the practice to screw the glass globe which encloses the lamp, into the metal base of the fixture, permitting it to seat itself upon a soft gasket of rubber insertion. In other countries a flange is cast on the bottom of the glass globe and a ring of metal compresses the globe upon the gasket. Steam-tight fixtures are made in several models to adapt them to certain locations and to facilitate installation. Fixtures for oil-carrying vessels differ slightly from the ordinary steam-tight fixture, the principal difference being that in the former case the globe is cemented to a metal ring which makes a tight screwed joint with the base; practice among the owners of oil vessels does not agree as to their use. Fixtures for living spaces are generally selected by the owner, and are similar to those in vogue on land except that they must be designed for mounting on a flat block and must permit ample room in the base for connections. Recently china fixtures (Beleek) have been introduced in lieu of metal for passenger quarters. The advantages are incorrodibility and cleanliness.

102. Lamps. At the present time carbon-filament incandescent lamps are usually installed, but the tendency to use metallic filament lamps is gradually increasing. The successful use of wire-drawn tungsten lamps in railway car lighting is having its effect upon the rapid introduction of this type of lamp on shipboard; in addition to this, the smaller lamps at 110 volts permit a wider distribution with the same amount of copper.

103. Methods of illumination. The application of modern methods of illumination does not progress rapidly in this class of work. Conservatism plays a large part in abating any radical departures from present practice. A recently completed excursion steamer was largely equipped with indirect and semi-indirect fixtures, but in making such applications this type of vessel must not be confused with ocean-going vessels, which must so be fitted that such appliances will not be affected by the rolling of the ship.

104. Motor circuits. Feeders are led directly from the main switch board to a double-pole switch and cut-out placed in the line to protect the starting box and motor. The conductors must be designed to care for the starting current, especially if the circuit is so fused. The cut-out switch and the double-pole switch are not necessary for motors of 0.25 h.p. or less.

105. Motor controllers. Starting panels, similiar to those of land practice in their electrical features, but usually enclosed in a non-water-tight sheet metal box, are provided for all motors of capacities below 10 h.p.; for larger capacities, drum-type controllers are employed. The latter are protected either by separately mounted circuit-breakers or by specially designed contactors likewise enclosed in a sheet-metal box. This box must be made completely water-tight if mounted on an exposed deck.

106. Motors. Ordinarily land motors of regular commercial design are accepted and installed, but such practice is not deemed advisable from the standpoint of the engineer. Motors should be fully enclosed if located in exposed places or in the machinery spaces. Careful consideration should

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be given to the design of the bearings, especially the guards which prevent oil from travelling along the shaft and into the armature windings. The spaces in a vessel are usually crowded, and therefore the design should provide easy means for overhauling. Although not a universal rule, it would be conservative to specify that all motors should be built with horisontally split frames.

107. Searchlights. This apparatus, because of the comparatively large current consumed, is considered as furnishing part of the power load. The searchlight is served through a separate switch on the main switchboard, and the arc voltage is adjusted by an external variable resistance. Provision is made on the switchboard whereby the voltage of the searchlight feeder may be observed by use of the generator voltmeter. The searchlight may be managed from the pilot house by either direct hand control or remote electric control. In order to insure against the ill effects of radio-telegraph induction it is necessary that exposed leads to searchlights be either encased in pipe or wrapped with wire. In both cases the outer steel covering must be well grounded to the hull of the vessel. Searchlights are useful in picking up buoys in harbor channels and, in some trades, are very necessary for loading and unloading at night. For freight vessels or for passenger and freight vessels of 4,000 tons carrying capacity or over, the searchlight should not be less than 18 in. in diameter.

108. Electric radiators. For certain service, such as the coastwise traffic of the Pacific coast, electric air heaters find a suitable application. Where the temperature varies but a few degrees, as in this instance, passenger steamers can thus be comfortably heated without exceeding proper temperatures. For attractiveness some vessels carry luminous radiators in the state-rooms and lounging rooms, and tubular air heaters in the passageways and in the rooms less frequented. These appliances must be designed to undergo hard service, must be properly fused, arranged for mounting on bulkheads, and should be sufficiently guarded to prevent inflammable materials from being cast upon them.

109. Engine telegraph system. For the maneuvering directions between the pilot house and bridge and the engine room, mechanical signals are employed. This system consists generally of transmitters, located one in the pilot house and one on the bridge, connected by low-brass wire and triple-link chain passing over brass pulleys to a receiver in the engine room. A reply system assures that the signal has been properly received. Occasionally an electrical attachment is made from the engine-room receiver to the reversing shaft of the engine whereby a false signal may be immediately made known. The transmitter dials are electrically illuminated. Various models to suit the propelling machinery are manufactured.

110. Miscellaneous mechanical telegraph and bell pulls. Other telegraphs for the purpose of docking the ship, steering, indicating the rudder angle, and for adjusting the mooring lines, are exactly similar to the engine telegraph instruments except that the dial orders are suitably changed. As an emergency precaution mechanical bell-pulls are installed near the engine telegraphs, connecting with a gong and a jingle bell in the engine room. As an auxiliary to any means for operating the main steam-whistle valve, mechanical pulls are located on the bridge and in the pilot house.

111. Telephone speaking tubes and call-bell system. The law requires that for vessels in which the distance from the pilot house to the engine room is greater than 150 ft. a telephone must be installed in addition to, or in place of, the voice tube. For shorter distances speaking tubes are used giving communication between important places in the vessel. It is compulsory to install either a speaking tube or a telephone between the wireless room and the bridge. Other points of communication are merely for convenience and differ with the desires of the owner. In both passenger and freight vessels, annunciators are located in the main pantry and push buttons are installed in all staterooms, messrooms, saloons, etc. In living quarters remote from the bridge and not provided with watchmen on continuous duty, alarm gongs are installed; these are actuated by a push button located in the pilot house. This is a requirement of law.

112. Fire-alarm system. All vessels are not equipped with such a system, and the systems that have hitherto been installed have not proven altogether satisfactory. Such systems usually consist of electrical contacts which are closed by the melting of a fuse of soft metal, and merely indicate the presence of fire. Two systems are on the market to-day which more nearly approach

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satisfactory service. In one of these not only is warming of the exact locatio of the fire given, but live steam is admitted to the origin of the fire by mean of a direct lead of pipe.

113. Submarine signals. Large cast-brass bells, rung either by electri air or wave power, are submerged beneath the lightships that beacon th coast, or may be suspended from a buoy which serves the same purpos On both the starboard and port bow down in the forehold of a sea-going vessel are placed two tanks filled with brine. A diaphragm transmitter i placed inside each tank and is connected to telephone receivers located i the pilot house.* A double set of batteries are included to avert interruptio to the service. Submarine signals can then be easily detected for a rang under favorable conditions of at least 6 to 8 miles by this electric perception of water vibration when the bell is struck. As there is a receiving station on each side of the bow, it can also be determined whether the vess is approaching the port or the starboard side of the beacon. Experiment are now being made to render practicable the use of high-frequency impulse through the water, so that full communication can be established betwee vessels. For description of Fessenden Submarine Oscillator see *Trans.* A. I. E. E., 1914.

114. Electric-whistle operator. This device consists of an electro-magnet operating a sensitive steam valve directly connected to the ma steam whistle. By means of a clock movement the whistle may be blow automatically as well as at will. A telegraph key is also provided so tha code signals may be given from the whistle. With an additional contact disc on the clock movement and an external switch, automatic signals can b given from a ship alone in a fog, as well as complying with the law whe towing another vessel.

115. Radio-telegraphy and radio-telephony. All systems which are explained elsewhere (Sec. 21) and which are applicable for shipboard in stallation, are, of course, subject to the selection of the owner. The part of care of installation are very minor except the serious one of obtaining positive and sufficient ground connections. The effects upon the rigging of the vessel are such as to require careful grounding of all stay lines, etc., and as mentioned under searchlights (Par. **107**), all exposed conductors must be properly encased. This property of radio-telegraphy must also be con sidered in connection with the type of electric installation adopted.

116. Generating plant design. The generator is direct-connected to a special marine-type engine or to a turbine. The special features of design relate to reductions in weight and space. The manufacturers are prepared to supply generating sets suitable for this purpose, built with non-corrosive parts and proper arrangement of steam connections for ship installation. The generator frame is usually split horizontally, and easy access is afforded to the commutator. For both reciprocating-engine and turbine drive, forced lubrication is preferred. The present accepted voltage is 110 volts, and direct-current compound-wound generators are used. The prime mover must be able to exhaust either into the feed-water heater, the main or auxiliary condenser, or into the atmosphere. Owners do not agree as to the advantages of the two types of prime mover. Some object to the high rotative speed of the generator which in certain small sets is as high as 5,000 rev. per min.; others prefer the ease of operation and the reduction of upkeep of the turbine in comparison with the reciprocating engine.

117. Generating plant operation. Except in very large passenger and freight vessels, the dynamos are located in the engine room and are therefore under the direction of the engine division. Since they form one of the many auxiliaries it becomes evident that they must be reliable, rugged and able to operate with little attention. There are reciprocating engines now manufactured which combine the gravity-feed and forced-lubrication systems in such manner that the apparatus is reasonably "fool proof" as far as the oiling is concerned. On the generator end, if of open construction, a sheet-metal guard is placed over the commutator so that it is protected from mechanical injury. Incidentally this avoids the danger of any one being thrown against it in passing. These sets usually operate under favorable conditions, without undue noise, and the regulation is within 2 per cent.

* Fay. *Proc.* A. I. E. E., 1912.

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118. The cost of marine generating sets is not much higher than that of ordinary commercial sets of the same capacity. The average price is approximately $90 to $120 per kw.

119. Switchboards. Regular commercial practice is followed as far as general design and apparatus is concerned. Compactness is necessary so that the board may be mounted as near a bulkhead as possible. Owners differ as to the method of connections, some desiring that the generators be run in parallel; others preferring that each feeder be provided with a double-throw switch and that separate bus bars be provided for each generator. This is more a question of operation than one of engineering, but with the conditions as described in Par. 117 it would seem more desirable to keep the generators on separate bus bars, should no electrician be carried.

120. Conduit and moulding. The special requirement for any marine installation is that the conductors be so protected that grounds will seldom occur and that the water-tightness of the vessel will not be impaired. All of the above cited rules require a heavy insulation of rubber and furthermore require that the completed installation must show approximately one megohn of insulation resistance. Beyond these rules the owner usually specifies the highest quality of wire upon the market. As it is customary to use enamel-lined conduits, double-braided wire is installed in conduits and single-braided wire in mouldings. In a combined conduit and moulding installation, conduits are run on exposed decks, in cargo holds, machinery spaces, galleys, pantrys, crew's quarters, etc. Water-tight junction boxes for branch connections and steam-tight fixtures are used on such lines. In the living quarters, mouldings matching the woodwork are provided, all connections being carefully made and laid in the moulding. When conductors pass through steel beams or bulkheads the hole is bushed with hard rubber. When conduits pass through water-tight decks or bulkheads a brass stuffing tube is fitted at the bulkhead; this tube is packed with red lead and flax, forming a water-tight joint.

121. Flexible cables and conduit. Flexible cables with or without a lead covering are sometimes used in lieu of mouldings. The flexible cables are strapped on the structure, have the advantage of being readily overhauled, and, if the insulation is properly selected, reduce the amount of inflammable material.

122. Steel braided armored cables. There is at present on the American market a design of steel-armored cable similar to that used for some time past in foreign countries. This material supersedes both conduits and mouldings, as the lead-covered steel-armored cable is perfectly water-tight and sufficiently protected for exposed spaces; the armored cable without a lead sheath is applicable for living spaces where it may be safely run behind panel work or in decorative mouldings. As mentioned above, this type of installation besides having the important characteristic of reducing grounds to a minimum also makes a perfectly safe installation for heavy wireless telegraph outfits. The only change necessary in fittings is that stuffing tubes must be added to the water-tight branch junction boxes.

NAVAL PRACTICE

123. Lighting system. All governments strive to obtain for their naval vessels the very latest and best developments of the art. This desire precludes standardization to any great extent. The methods of distributing light, the type of lighting fixtures, and the problems of illumination are all being carefully studied; advances in the art are rapidly adopted. In general the fixtures are heavier than in ordinary practice, and the materials, as specified, are more closely inspected. In the United States Navy, the standard lamp is rated at 123 volts, and metallic-filament lamps are now in service. Arc lamps are no longer used, having been superseded by the 250-watt tungsten lamp.

124. Motor system. Motors and their controlling equipments are elaborately specified, tested and inspected by the United States Government. Copies of these specifications as well as all apparatus and material furnished the United States Government may be procured upon application to the Navy Bureau concerned. Within recent years the motor load on a battleship has very greatly increased both in capacity and importance. This augmentation has caused some governments to increase the generator voltage

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to 220, still retaining direct current. Such auxiliaries as the anchor windlass requiring 300 rated horse-power, and the steering gear which requires approximately a like amount, illustrate the above statement.

125. Signalling system. Although the lighting and power systems are large and important, they are not more important than the interior communication in a battleship. Every device that human ingenuity can devise is called into requisition, and its operation and efficiency are carefully observed if it is of value it is regularly employed. Systems of signals connect the important points for use in navigating the ship, in transmitting general orders and in the firing of the guns. Mechanical signals parallel all important electrical signals.

126. Generating plant. The U. S. Navy has adopted as standard a direct-connected horizontal steam-turbine generator set operating at a standard direct-current voltage of 125.* Reliance is placed on a strict interpretation of the specifications to produce a perfect machine with as small a weight and as high an efficiency as the manufacturer can guarantee. Nations differ as to the proper number of dynamo rooms and to the number of machines which should be contained in them. The U. S. Navy prefers to-day two rooms with two dynamos in each room. Switchboard practice likewise varies in the different countries.† Some of the foreign powers use steel for mounting the various switching devices, but the U. S. Navy now specifies special composition. In some naval vessels the generator control switchboard is located in the dynamo room, and in other vessels it is combined with the distribution switchboard located in an adjacent compartment.

127. Wiring. Many of the foreign nations have for several years been using steel-armored, lead-covered cables and now the U. S. Navy has adopted a similar system. Previous practice in the U. S. Navy was generally to install conduits and to use open wires only in those places not subject to mechanical injury. The appliances are all specially standardised, specified and inspected, and are in every way more rugged and of better metal than in the ordinary merchant service.

In some installations the material and apparatus may be delivered as the work proceeds, but precautions are essential when the installation of steel-armored cables is undertaken. In such an installation the cables are laid instead of pulled into conduits. This consideration together with the fact that it is not wise to expose the loose end of the cable for any length of time requires that all apparatus and material be fully delivered before starting the installation. In ordering wire for shipboard installation it must be remembered that the length of wire on the standard reels of the manufacturer may vary greatly, increasing the cost of material due to the waste in cutting off the proper length. It has been found desirable and economical to order wire in positive lengths, placed upon reels marked with the feeder or main number as shown on the approved drawing.

MISCELLANEOUS

128. Cost of electric plant on typical vessels. Actual costs of such installations are not obtainable and would not be of material value. Estimated flat costs for different types of vessels are here given as a guide.

Tug boat, 50 lamps, 3 kw	$2,000
Ferry boat, 300 lamps, 20 kw	$5,000
Freight vessel, 150 lamps, searchlight, 20 kw	$8,000
Oil tanker, 150 lamps, searchlight, 20 kw	$10,000
Passenger & freight vessel, 1,200 lamps, searchlight, heating system, 150 kw	$50,000
Battleship, 3,000 lamps, 1,500 kw	$1,900,000

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* The U. S. Gov. has recently (1914) adopted 230 volts as standard.

† Dynamo arrangement now (1922) conforms with the design of engine room in electrically propelled battleships.

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APPLICATIONS OF ELECTRICITY IN THE UNITED STATES ARMY

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130. General applications. Aside from the usual applications to illumination and the operation of machinery, electrical energy is employed in the Army for communication, operation of searchlights, maneuvering seacoast guns, operating ammunition hoists, blasting, exploding mines, firing guns, and electrifying barbed wire entanglements.

131. Energy supply. A central generating plant would be the most economical arrangement, but might be paralysed by a single well-directed shot. To provide for such an emergency, a reserve supply is necessary. Where reserve energy supply is not already provided for in other ways at seacoast forts, it is current practice to install 25-kw. gasoline generating sets in or near the batteries. Commercial supply also is used when available. On account of the development of the gasoline sets, the use of storage batteries in fortifications is being discontinued; these batteries were formerly required for supplying the telautographs, but are now employed only in connection with certain telephone, radio, and submarine mine systems.

132. General specifications for power plants in fortifications. The National Coast-Defense Board, in 1906, recommended: (a) that the electrical energy used for fortification and defense purposes be furnished by an adequate steam-driven, direct-current central power plant, all machinery to conform in type to approved commercial standards; (b) that each battery or group of batteries be equipped with gas-driven or oil-driven direct-current generators, installed as a reserve to the central plant; (c) that the energy supply of searchlights be provided by self-contained units unless the searchlights are in close proximity to the central plant; (d) that the torpedo casemates be supplied with energy from independent sources for submarine-mine purposes; this arrangement should constitute an integral part of the submarine-mine defense; (e) that alternating current energy, when essential, should be obtained from the direct-current distribution system, using for the purpose a suitable converter; if, however, it is found more economical, this energy may be obtained from a separate alternator; (f) that the central-station output, when not needed for fortification service, may be used for garrison purposes, provided that the latter load does not require too large an increase in the size and number of units; (g) that, should the garrison service require an alternating-current distribution system, the energy should be supplied from the central plant, either through a suitable converter or from alternators installed for this special purpose in the central station; (h) that uniformity of types and accessories should be adhered to as closely as possible.

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133. Protection of distribution. Considerations of economy, efficiency, and protection against hostile fire require that the greater part of the electrical communications be either subterranean or submarine. When underground, conductors are laid in trenches, or in conduits. In trenches conductors should be lead-covered and armored, the armor being served with a jute yarn in some cases. Lead-covered, unarmored cable without jute on the lead covering, is suitable for conduit construction.

134. Wiring specifications. The wiring rules formulated by a Board on Standardization of Wiring for Seacoast Batteries are as follows: (a) conduits should not be employed for local distribution in emplacements where their use can be avoided; (b) all wires leading out from the emplacement switchboard should be exposed in so far as possible; (c) armored cable should be used for all exposed wiring, and lead-covered cable should be used in conduits; (d) all branch lighting circuits in emplacement distribution will be of No. 12, A.W.G.; (e) exposed wires will be supported on ceilings or walls with cable hangers, to permit the application of preservative coatings; (f) snap-switch and plugging-in boxes introduce more points where grounds may occur, and should be used only where they are absolutely essential; (g) a branch lighting circuit may carry a maximum current of six amperes to obviate having too many lamps on one branch circuit, and consequent inconvenience in case of failure of one branch); (h) all fixtures for inside or outside lighting about emplacements should be of approved water-tight type. Due to the effect of alkalies on the lead covering of cable, concrete conduits are no longer installed. Condensation and other sources of dampness in the seacoast fortifications render particular care necessary to prevent grounds.

135. Special illumination of range-finding instruments. The cross wires and range scales of position-finding instruments are illuminated by electric lamps; emergency lamps are supplied with energy from dry cells. Oil and gas illuminants have been found unsuitable for this service. At seacoast forts information regarding range and declination may be transmitted from plotting rooms to gun crews by means of electrical indicators, some of which operate on the principle of the electric carriage call in use in theatres.

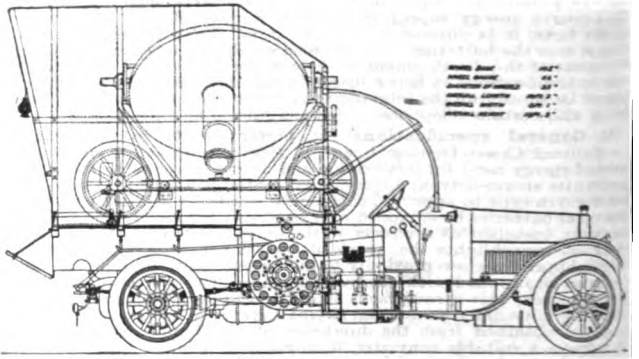


FIG. 22.—Mobile searchlight power unit for 60-in. light, open (dishpan) type.

136. Searchlights are used in the coast defenses for signaling; for discovering and illuminating the enemy's ships and aircraft; for bewildering his pilots; and for rendering his searchlights ineffective by means of fixed beams from the shore, which the enemy's beams cannot easily penetrate. In land operations the main function of the searchlight is to illuminate hostile aircraft. It is difficult to use searchlights for foreground illumination, due to

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he long range and effectiveness of artillery. They indicate landing places for aircraft, and may also be used to mark aerial routes. The searchlights now standard are the so-called 60-in. (1.5 m.) and the 36-in. (90.0 cm.). The mirrors are ordinarily of glass, parabolical in shape, and with silvered backing. A 25-kw. gasoline generating set is furnished for operating each 60-in. (1.5 in.) seacoast searchlight. A 20- to 25-kw. generator, operated by the engine of a motor truck, furnishes power for mobile searchlights.

The ranges at which targets may be satisfactorily illuminated by a 60-in. (1.5 m.) searchlight are as follows: with very clear atmosphere, 10 miles (16.09 km.) and sometimes farther; with average atmosphere, 5 to 7 miles (8.05 to 11.27 km.); through slight haze, 2 to 3 miles (3.22 to 4.83 km.); in medium haze or gray dawn, 1 to 2 miles (1.61 to 3.22 km.).

Remote control of searchlights may be effected by use of a synchronous-motor controller, using 110 volts at the training motors, and may be accomplished at a distance of 2 miles (3.22 km.).

137. Signaling by searchlight may be accomplished by day or night by exposing and occulting the beam with a shutter, thus sending a series of dots and dashes that are visible, in ordinary weather, for a distance as great as 10 miles (16.09 km.) at sea. At night the beam may be traversed, turned on the clouds, or reflected from a water surface. If the searchlight is depressed too far, the heat may damage the mirror. If used in cold weather, the mirror should be heated and cooled gradually, because rapid expansion or contraction may cause the silvering to flake.

138. The Ardois system is a vertical display of four lights, manipulated by a keyboard. Red and white lights represent dots and dashes, respectively.

139. Telephone and telegraph. The telephone is extensively used in the army, particularly in connection with range-finding and fire-control. In field operations it plays an important part in the transmission of information, orders, etc. The telegraph is of less importance, and is used in the same manner as in commercial practice.

140. Buzzer. This apparatus consists of an interrupter and an induction coil supplied with energy from a few dry cells. In operation the buzzer is used as a transmitter for the purpose of signaling, the frequency of the current being such as to produce a high note in a telephone receiver at the far end of the signaling circuit. Leaks, bad connections, and high resistances, any one of which would cripple a system employing Morse instruments, merely affect the loudness of the signals in the receiver. Each transmitting station is equipped with a telegraph key and a telephone transmitter, and may be used either for telegraph or telephone communication.

141. Data on Searchlights

Size of light (inches)	Type		Arc		Electrodes, size in millimeters		Time of burning, (hours)	Controller
	Intensity	Mounting	Volts	Amperes	Positive	Negative		
60	High	Barrel	75	150	16 × 915	11 × 407	2.5	Synchronous motor
36	High	Barrel	75	150	16 × 457	11 × 330	1.3	Synchronous motor
60	High	Open	75	150	16 × 380	11 × 215	0.83	Hand
60	Medium	Open	65	200	284 × 280	16 × 153	0.93	Hand

The high intensity lights have the carbons rotated and also air cooled.
The open (dishpan) type lights are hand controlled, and weigh about 800 lb., as compared to 5,500 lb. for the 60-in. (1.5 m.) barrel type.

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142. Wireless (radio) telegraphy and telephony are readily adaptable to military purposes, and for ordinary distances can take the place of the telegraph and telephone, making them particularly useful in field operations. In Alaska, on account of the frozen soil, and in rocky country satisfactory grounds are sometimes difficult to obtain. A counterpoise is always supplied for use in the field. The Signal Corps has developed portable radio **telegraph sets** that may be transported by men, on mules, on wagons or motor trucks, and on dirigible balloons or airplanes. These sets have **ranges** of 5 to 7 miles (8.05 to 11.27 km.), 60 miles (96.56 km.), 5 to 1,000 miles (8.05 to 1,609.35 km.), and 50 to 1,000 miles (80.47 to 1,609.35 km. respectively. Radio **telephone sets** for wagons or motor trucks have a range of about 400 miles (643.74 km.); for dirigibles or airplanes, 1½ to 100 miles (2.41 to 160.93 km.). Depending on type, the generator of the sets may be hand driven, storage battery driven, engine driven, or fan driven. With one exception, radio telegraph sets in the Army use vacuum tubes as the source of undamped waves. Practically all **detectors** are vacuum tubes. On airplanes, receiving is difficult on account of the noise of the engine, necessitating higher amplification on the plane than on the ground, and increased power on the ground. Radio **direction finders** are used considerably in the Army. One type of finder consists of two closed loops mounted on the wings at right angles to each other and operating on a maximum signal. When flying at a height of 2,000 ft.;(609.6 m.), it was possible to guide the airplane exactly over the transmitting station; while it was easy at that height to detect when the airplane passed as small a distance as 100 ft. (30.48 m.) from directly over the transmitting station. Radio **beacon stations** should be limited in range to 30 miles (48.28 km.) along the coasts and borders, and to 50 miles (80.47 km.) in the interior, except where a multiplicity of stations would be uneconomical.

143. Handling of guns. For enabling seacoast guns to be traversed by power, motors are attached to some of the gun carriages. When, at drill, the guns on disappearing carriages are tripped into battery without being subsequently fired, the retracting to the loading position may be done by motors. Retracting motors can also be arranged to elevate or depress the muzzle of the guns when being aimed. By means of an electric motor, compressed air is supplied to operate the breech-block and to clean out the gun after firing.

144. Firing of seacoast guns may be accomplished electrically or by pulling a lanyard. To guard against accidents in electrical firing, there are usually three breaks in the circuit. Two are closed automatically: one when the breech-block is properly locked, and the second when the gun has moved properly into battery; the third is a contact which is manually closed at the firing pistol or switch when all is in readiness. Energy may be supplied from dry cells or an electric exploder.

145. Ammunition hoists are used for raising projectiles from the magazine level to the loading-platform level of some of the larger guns; these hoists consist of endless sprocket chains, with carrier arms attached, operated by electric motors. To avoid accidents, the motors cannot normally be reversed, but the projectiles can be lowered by hand. The powder charges may be handled on special hoists.

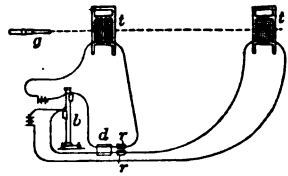


FIG. 23.—Velocity recorder.*

146. The velocity of a projectile is measured by firing it through two targets *t*, Fig. 23, separated by a known distance. An electric circuit is broken at each target, and the elapsed time between breaks is determined with a Le Boulengé Chronograph (*b*, *d*, *r*). The velocity of gun recoil can be similarly determined.

147. Targets. The face of a self-scoring target for rifle practice is divided into segments of armor plate, which the rifle bullet cannot penetrate. Held against the backs of these sections by springs are one or more spindles. A bullet striking a segment causes the spindle or spindles abutting against

*Lissak, O. M. "Ordnance and Gunnery;" New York, Wiley and Sons, 1906.

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that segment to jump backward, closing an electrical contact; this causes a number representing the value of the hit to appear in a corresponding place on a miniature-target annunciator at the firing point. Dry cells furnish the energy required for operation. Each segment has a separate circuit, but with a common return.

148. Electrical caps, or fuses (Fig. 24) usually contain fulminate of mercury, with a platinum bridge, *p*, imbedded in the fulminate; heating the bridge by passage of an electric current through it causes the ignition. Caps stored in a damp place deteriorate rapidly. With less than 0.25 per cent. moisture, the caps will not explode dynamite, although they may themselves explode. The tetryl electric cap is necessary to insure detonation of triton (trinitrotoluene). The tetryl in the cap is detonated by a small charge of mercury fulminate, which is detonated by heat caused by a current passing through the bridge. A tetryl blasting cap with 12-ft. (3.65 m.) lead wires has a resistance of 1.5 ohms and requires a current of 0.4 amp. for detonation. The standard blasting machine used in the Army will surely detonate 12 tetryl caps in series. The machine generates 2.5 amp. at 45 volts with ordinarily vigorous use. For simultaneous ignitions, caps are usually connected in series; however, owing to non-uniform sensitiveness, one or more may explode and break the circuit before the bridges of the others have become sufficiently heated. Where several caps are to be exploded, and where sufficient energy is available, it is best to connect them in parallel. The leads should be insulated, though this is not imperative, as fuses have been fired with bare leads in fresh water. The wire should be of copper, of a size not smaller than No. 18 A. W. G., where the distance is 500 ft. (152.4 m.). Circuits arranged for electric detonation should be left open until just before detonation. Closed circuits are likely to cause detonation by induced currents from nearby electrical conductors or from lightning.



FIG. 24.—Exploder.*

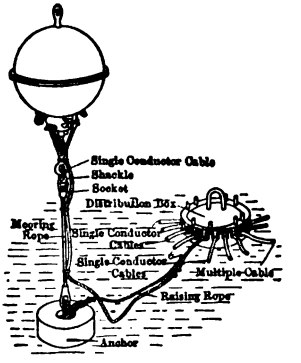


FIG. 25.—Buoyant mine.*

149. Mines are of two general classes, land and submarine. The former consist of charges of explosive below the surface of the ground. By means of electric fuses and leads these can be fired at the will of the operators, while also being arranged to explode by contact, as when run over by a tank or armored car. Submarine mines (Fig. 25) contain charges of high explosive which it is desirable to explode as near as possible to the hull of the enemy's ships. Such mines may be anchored so as to float below the water surface, or may be free to drift. The inside mechanism of the fixed or anchored mines is so designed as to allow of frequent and safe testing of the fuses after the mines have been planted.

* Lissak, O. M. "Ordnance and Gunnery;" New York, Wiley and Sons, 1908.

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Electrical firing may be effected as follows: (a) when the mine is struck by a ship, the power circuit being inside and rendered operative by the jar or tipping; (b) at will from the shore, either with or without an electrical signal from the mine; (c) automatically when struck, provided a switch on shore is closed at the time, the circuit being finally completed by the striking of the floating mine-case. The methods cited in (b) and (c) permit friendly ships to pass with impunity, provided the switch on shore is not closed.

150. Bibliography. "Report of the National Coast-Defense Board;" Washington, Government Printing Office, 1906.

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ELECTRICITY AND PLANT GROWTH

By JOHN E. NEWMAN

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151. General. In the eighteenth century a Scotchman subjected myrtles to the discharge from a frictional machine and reported that they were benefitted. Since his time there have been many experiments, but they may all be divided into two main classes, as follows: (a) those aiming to influence the plant by changes in the atmospheric electrification; and (b) those in which currents are passed through the soil about the plants. The records of these experiments show that, generally speaking, where artificial discharges of electricity to the air over the plants take place, favorable results have been recorded; where the method has been that of passing currents through the soil, the results are contradictory.

152. The first systematic experiments on any important scale are those of the late Prof. Lemstrom, of Helsingfors University, Finland, who carried out experiments on a field scale in Finland, France, Germany and in England (at Durham University). In the course of his trials, he experimented with almost all the common vegetables and cereals as well as with strawberries and raspberries. His method was to suspend a network of fine iron wires, spaced about 4 ft. apart, 16 in. above the plants to be electrified. These wires were provided with points like barbed wire, and had to be raised as the plants grew. While the results showed a definite increase from 20 per cent. to 45 per cent. in the case of most crops, the method is impracticable for work on a large scale. The close network of wires about 1 ft. above the crop and the numerous posts necessary, seriously interfere with the ordinary cultivation of the ground and make horse or steam cultivation impossible. Nor can an influence machine be considered practical from an engineering standpoint.

153. In the Evesham experiments, commenced in 1906 (and still being carried on) by the writer, in cooperation with Mr. R. Bomford and Sir Oliver Lodge, the following arrangements were adopted and have been followed essentially in subsequent installations in different parts of the world, including the plant now being worked by the Department of Agriculture at Washington. Over the area to be electrified is erected a wire network consisting of thin galvanised steel or bronze wire run at an average height of 15 ft. above ground (this being assumed as that clearance which would allow a loaded harvesting wagon to pass underneath), the wires being 10 ft. apart and carried as span wires between stout telegraph wire, on insulators mounted on posts planted 71 yd. apart in parallel rows 102 yd. apart. Thus 21 poles will do for 20 acres, or roughly a pole to an acre.

154. The potential at which the network is charged varies from 50,000 to 75,000 volts. This corresponds to the potential at which the network is actually charged by an average thunderstorm, and at this pressure the discharge on a quiet day is distinctly audible. What we have is practically a leaky condenser, with the air as the dielectric; and this condenser must be kept charged.

155. Source of energy. The current to charge the network is provided by an induction coil, the negative high-tension pole of which is earthed and

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the positive high-tension pole connected to the network through from 3 to 5 **Lodge valves** in series. The valves will allow positive electricity to pass through them in one direction only, and negative electricity to pass through them only in the other direction. Any value of direct-current voltage up to 250 may be employed, or alternating current may be used, with some decrease in efficiency.

156. A motor-driven mercury gas break, able to run about 1,000 hr. without being cleaned out, is used; it is equipped, when necessary, with an automatic hydrogen generator.

157. The power absorbed by the coil when charging a network of 25 acres is about 300 to 500 watts, and the small break motor and ventilating fan motor absorb another 100 watts.

158. The best length and time of application of the current is still a matter for experiment and may possibly vary with different crops or in different climates, but so far it appears as if an application of from 4 to 6 hr. per day gives better results than a longer period.

159. Effect of moisture in soil. It is not yet possible to accurately predict the results which will follow electrification, but it can be said that its application is probably useless in dry regions, and that the most favorable results will follow where there is ample moisture in the ground.

160. Results of application. The process has been applied thus far chiefly to wheat, potatoes, sugar beets and strawberries.

Wheat, during eight successive years (1905–1911), in three fields on Mr. Bomfords farm at Evesham, England, has given an average increase of 21 per cent. in weight of grain, and also an increase of straw which it has not been possible to measure. The only year in which no increase resulted was 1911, which was a year of great drought in England, and the yield during this period from both electrified and control areas was only 16 bu. per acre.

Potatoes have shown more irregular results, affording, at an installation at Dumfries, Scotland, increases of 20 per cent. to 25 per cent. in two seasons, and showing no difference in a third. In the last case, the control and electrified plots were arranged in a chess-board pattern, and were of moderate size. Subsequent tests showed that one or other of the control plots was usually being electrified unintentionally. In the two years during which positive results were secured, there was but one control and one electrified plot.

Outdoor strawberries have shown a small decrease, or no difference, which is contrary to the results obtained with forced strawberries in pots in greenhouses. This result may be due to the dwarf-growing habit of the plant, although it should be noted that the control and electrified areas in this case also were arranged chess-board fashion, and that the yield from the whole field was above the average. The electrified fruit was markedly sweeter than the unelectrified.

Sugar-beets at several European installations have displayed increases of 20 per cent. or more, with a considerable increase in the sugar content of the roots.

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WINDMILL ELECTRIC PLANTS

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162. Wind velocities are customarily recorded, in the stations of t U. S. Weather Bureau, by means of the Robinson anemometer whic integrates the total wind movement. The records of the Weather Bure should be consulted for definite data on wind movement in any particul locality. The measured or indicated wind velocity, as recorded by t Weather Bureau, is not the true velocity, but

$$\log V = 0.509 + 0.9012 \log v \qquad (1$$

where V is the true wind velocity and v is the actual velocity of the c centres in the anemometer. See *Electrical World*, Vol. LVI, Oct. 27, 191 pp. 995 to 1000. As a rule, the measured or indicated velocity is the o implied in discussions of velocity and pressure.

163. Wind movement is recorded in miles, and is virtually the int gration of the instantaneous velocities for a given period or the total distan a given particle of air would move in that time. Tables of wind movemen per day or per month have been prepared and published for various localitie many of these can be found in the government publications. Such info mation is very essential to any careful study or forecast of the probab performance of a windmill in any specific locality.

164. Wind pressure and its relation to wind velocity is a subject whi has received much study by many investigators. The Weather Bure formula is

$$P = 0.004\left(\frac{B}{30}\right)V^2 \qquad \text{(lb. per sq. ft.)} \qquad (2$$

where B is the barometer reading in inches of mercury and V is the indicate velocity in miles per hr.

165. Available work in air currents. The total aerostatic head a moving gas, at any given point, is the sum of the pressure head and its velocity head. Since the aerostatic gradient changes but slightly betwe areas of high and low pressure, it is sensibly constant in passing any giv locality. Therefore the total available work stored in the moving ga represented by the velocity head, or energy of momentum.

166. Windmill characteristics are shown in Figs. 26 and 27, plotte from the test data on a 16-ft. aermotor (steel mill) taken from Par. 1 It is obvious from Fig. 26 that both the speed and the load torque increa

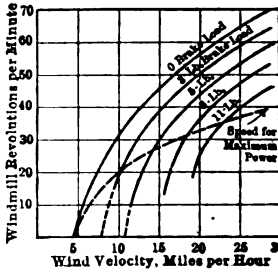


FIG. 26.—Speed curves of 16-ft. Aermotor.

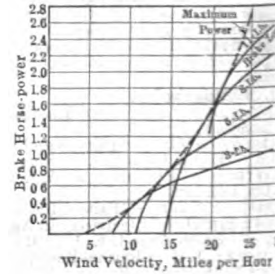


FIG. 27.—Power curves of 16-ft. Aermotor.

with the wind velocity, for maximum output; this is made even clearer b the maximum power curve in Fig. 27. Maximum output therefore requir that the load on the mill, under variable wind velocities, shall have th characteristic of increasing torque with rising speed, in a certain definit manner for any given mill.

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107. Table of Test Data on Vertical Windmills

(Water Supply and Irrigation Paper, No. 42, Part II)

Diam. and make of mill	Load on prony brake (lb.)	Rev. per min. at different wind velocities					Horse-power output at different wind velocities					Air temp. deg. Fahr.	Barometric pressure (in.)	Number of sails	Angle of sails (deg.)
		8 mi.	12 mi.	16 mi.	20 mi.	25 mi.	8 mi.	12 mi.	16 mi.	20 mi.	25 mi.				
12-ft. Aermotor (steel)	0	30	49	63	75	87	0.000	.....	.....	.....	.....	46	28.9	18	31
	2	16	43	57	70	81	0.089	0.285	0.386	0.458	0.523				
	4	....	23	48	65	77	.....	0.303	0.653	0.890	1.02				
	6	....	....	12	50	72	.....	.....	.....	1.03	1.45				
12-ft. Ideal (steel)	0	25	40	51	60	68	0.000	.....	.....	.....	.....	92	28.7	21	32
	1.5	....	29	41	51	60	.....	0.239	0.338	0.420	0.500				
	2.5	....	....	32	44	54	.....	.....	0.440	0.606	0.745				
12-ft. Monitor (wood)	0	16	33	44	54	64	0.000	.....	.....	.....	.....	83	28.6	96	34
	1.5	....	25	35	43	52	.....	0.091	0.127	0.156	0.189				
	2.88	....	....	27	34	40	.....	.....	0.230	0.324	0.381				
	4.5	....	....	10	24	30	.....	.....	0.150	0.357	0.445				
16-ft. Aermotor (steel)	0	23	38	48.0	56	64.5	0.000	.....	.....	.....	.....	84	28.8	18	30
	3	....	28	41.0	50	58.5	.....	0.45	0.66	0.80	0.94				
	5	....	13	33.5	44	53.5	.....	0.35	0.89	1.16	1.43				
	8	....	....	16.0	36	47.0	.....	.....	0.68	1.53	2.01				
	11	....	....	.....	25	39.5	.....	.....	.....	1.47	2.31				
22.5-ft. Halliday (wood)	0	11	20	25	30	32	.....	.....	.....	.....	.....	82	28.7	144 in outer ring, 100 in inner ring	25
	1.5	6	16	22	26	30	0.059	0.163	0.217	0.257	0.296				
	5.0	....	11	18	22	26	.....	0.342	0.593	0.724	0.856				
	9.0	....	2	10	15	19	.....	0.118	0.593	0.890	1.126				

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168. Efficiency. The 12-ft. aermotor (Par. 167) in a 9-mile wind a maximum power, had an efficiency of 26 per cent.; this value was computed from the basis of the total wind area of the wheel (12-ft. circle). In a 14-mile wind the efficiency was 23 per cent. Maximum efficiency always occurs with maximum power or output.

169. Windmill governors. Practically all forms of vertical mills are equipped with a form of device which throws them partially or wholly out of the wind, when the wind velocity exceeds a certain value. The effect is to prevent excessive or dangerous speeds in high winds or gales.

170. Comparison of different types of windmills. Murphy's tests led him to the conclusion that steel wheels are superior to wooden wheels; also that curved sails are superior to flat sails. Furthermore, a relatively small number of large sails will give higher efficiency than a large number of small sails, of equal total area. Steel mills are commonly employed except along the seacoast or in very damp climates, where corrosion is likely to give more than ordinary trouble.

171. Example of useful work performed in a given period. Based on the records of mean wind movement at Dodge, Kansas, from 1889 to 1893, Murphy estimated (Water Supply and Irrigation Paper No. 6, Part II, page 118) that steel mills (aermotor) would give the following performances.

Size of mill	Horse-power-hours per month		
	Mean	Maximum (April)	Minimum (November)
12-foot.....	338	461	245
16-foot.....	488	671	351

172. Height of tower. The mill should always be placed well above surrounding objects such as trees or buildings, at least 30 ft. On account of competition, the tower weights are kept as low as possible and for this reason steel towers sometimes lack stiffness; wooden towers are usually less objectionable in this respect. It is almost always economical to place the mill at an elevation of 50 ft. or more above the ground, not only to avoid obstacles to free wind movement, but also because wind velocities are known to increase somewhat with the elevation.

173. Generators applicable to windmill electric plants are described in Sec. 8, Par. 186 to 189. A shunt-wound machine, with variable-speed drive, requires an automatic regulator for maintaining constant voltage. The differential type of winding, applied to a machine for charging storage batteries, tends inherently to regulate for constant output with variable-speed drive. It is also possible, with large mills, to employ two generators, one of small capacity for light winds and one of larger capacity for moderate winds, which both can be used in heavy winds.

174. Automatic battery switch. In order to connect the generator to the storage battery when the speed and the terminal voltage are sufficiently high, and to disconnect the generator when the speed and the voltage fall too low for charging, an automatic switch is employed whose functions are controlled by the terminal voltage of the generator.

175. Storage-battery reserve. The necessary reserve capacity in the storage battery, for any given installation, can be determined only by a careful study of the records of wind movement at the place in question. If the periods of calm occur frequently and last for any considerable time, it will pay to consider a gasolene engine for stand-by instead of the extra battery capacity required.

176. Comparative economy. In general the windmill electric plant in the present state of the art, cannot compete with energy supplied from central stations and its field is therefore restricted to rural districts and isolated regions. The annual operating expense, including interest, depreciation, taxes, repairs, oil and attendance, will probably range from 16 per cent. to 20 per cent. of the first cost. The charges for the electric plant will be reduced somewhat if the mill is used for other purposes, such as sawing

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wood, grinding grain and feed, pumping water, etc. A gasolene engine is frequently less expensive as a reserve or stand-by source of energy than a storage battery, especially for long periods of calm.

Many attempts have been made to design practical windmill plants for generating electrical energy for farm uses, but such plants have not as yet met with any marked commercial success in competition with the small gas-electric farm lighting sets which are now extensively used in rural districts where there is no central station service. An equipment recently placed on the market comprises a 14-ft. steel wheel, 1 kw. differentially-wound generator and 280-amp-hr., 32-volt storage battery, for which satisfactory results are claimed. The generated output of this plant, during a test of one month, was 60 kw-hr. The future possibilities of such plants undoubtedly depend in great degree upon the trend of the cost of gasolene and kerosene.

177. Literature on windmill electric plants. The literature on the subject is rather meagre and is scattered through many technical periodicals and publications. The following references are regarded as useful to anyone desiring further information.

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OZONE PRODUCTION

BY MILTON W. FRANKLIN

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178. General properties. Ozone is a colorless gas, in ordinary circumstances, possessing the odor of chlorine, or of moist phosphorus. In great thicknesses or under pressure the color is blue, and when liquefied it becomes a dark blue mobile liquid with highly magnetic properties. The chemical formula is O_3 and the molecular weight 48; the critical pressure is 125 atmospheres and the critical temperature, −103 deg. cent. It is an endothermic compound and the heat of formation is nearly 33,380 g-cal. per mole. At ordinary temperatures it is relatively stable but it decomposes in contact with organic, or in general, oxidisable matter, and spontaneously at 260 deg. cent. It is practically insoluble in water, 1.5 to 10 mg. per liter being the limits of solution at temperatures of from 2 deg. to 28 deg. cent., according to Maufang.

179. Formation. Ozone may be formed in various ways, which are: (a) by chemical action; (b) by electrolysis; (c) by the electrostatic field; (d) by ultraviolet rays; (e) by the radioactive elements; (f) by incandescent solids; (g) and by the evaporation of water. Only the production by the electrostatic field has been developed commercially. The theory of this method is not fully understood but it is probable that ionisation by collision

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takes place, with consequent dissociation of the oxygen which on recombination furnishes aggregates of ions consisting of molecules with an attached extra atom. Within working limits, in commercial ozone generators, the production is roughly proportionate to the electrostatic intensity above a certain critical value, and with alternating currents, to the frequency employed.

180. Chemical analysis. Treadwell and Anneler, in 1905, checked all previous results and finally established the correctness of the method of chemical analysis which is now in general use. This depends on the following reactions:

$$2KI + O_3 + H_2O = 2KOH + I_2 + O_2 \quad (3)$$

$$2Na_2S_2O_3 + I_2 + 2KOH + H_2SO_4 = Na_2S_4O_6 + 2NaI + K_2SO_4 + 2H_2O \quad (4)$$

In practice these reduce to the following volumetric equation:

$$1{,}000 \text{ c.c. } N/10 Na_2S_2O_3 = O_3/20 = 48/20 = 2.4 \text{ gm. } O_3 \quad (5)$$

The sample of ozonised air of measured volume is drawn through a neutral solution of KI and titrated with $Na_2S_2O_3$ or it may be collected in a calibrated flask and shaken with the neutral KI solution. The mixture of KI and I_2 is acidified with an equivalent of H_2SO_4 before the titration. It is customary to denote the amount of ozone in terms of gm. per cu. m. of air and to reduce the readings to spt.

181. Ozone generators have been made in various forms. The essential principle in all cases is the juxtaposition of two or more discharging surfaces so as to form a condenser with an air gap which may or may not be furnished with a dielectric element. The discharging surfaces may be smooth or armed with points, and if smooth they may be flat or curved. Ozonators without dielectrics generally possess rotating electrodes, so that they are in relative motion in order to avert sparking which favors the formation of nitrogen oxides and the destruction of ozone already formed. The great majority of successful ozone generators have smooth electrodes and dielectrics, and are divisible into two types, the cylindrical and the plate.

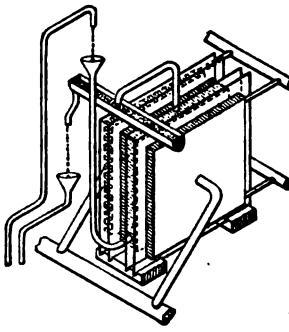


FIG. 28.—Plate ozonator.

182. A typical form of plate ozonizer is shown in Figs. 28 and 29. The two outer plates are piereed at the centre, and the ozonized air is aspirated through tubes inserted in the holes. The air enters at the peripheries of the plates and passes through the field to the centre. Cooling is effected by means of flat rectangular water boxes in contact with the two outer plates, and with a similar box n contact with and between the two inner plates. The two outer boxes are earthed; the inner box is insulated and forms the high-potential element of the ozonator. The boxes are all furnished with circulating water, that in the inner, high-potential box being introduced and removed by allowing the water to fall through the air a distance sufficient to ensure against wasteful electrical leakage. The whole structure is commonly contained in a glass retaining case into which suitable dry air is introduced. The advantage of this type of ozonator is that as the field is produced between the two glass plates, the labor necessary to keep the machine clean is nominal. The disadvantages are as follows: difficulty of assembling and taking apart, high potential required, complexity of the cooling system, large space occupied and danger of shut down of the whole system through the failure of one unit.

183. Operating voltages. Commercial ozonators are commonly operated on voltages ranging from 5,000 to 20,000 and at frequencies of from 50 to 500 cycles per sec., and are used in connection with transformers. Special high-frequency generators are generally furnished in all but the

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smallest installations, for the capacity of an ozone generator is almost proportional to the frequency employed.

184. Refrigeration of air supply. An essential to successful and economical ozonizing is dry dense air and consequently most installations, excepting very small ones, include a means for refrigerating the air. It has been found in practice that air cooled to about zero Centigrade possesses the requisite dryness, and that further cooling is uneconomical because, though the yield of the ozonator is increased, this is secured only at the expense of relatively greater cost for refrigeration.

185. Tubular ozonizers. A representative tubular unit is shown in Figs. 30 and 31. This consists of a cast-iron frame with two closed bulkheads connected together by the ozone tubes in much the same way as in a water tube boiler. Within these tubes, which are of glass, the cylindrical high-potential electrodes are placed coaxially. The outer tubes are immersed in water which forms the ground element, while the inner high-potential elements are connected to the circuit by means of suitable contacts on a bus bar which is carried into the air header through insulating bushings. The air is introduced into the rear header and passes through the tubes to the front, whence it passes into the ozone collecting pipe. This machine requires cleaning from time to time, but the operation is simple and quickly performed. The door of the ozone header is removed, the inner electrodes are drawn out and the tubes are cleaned with a swab.

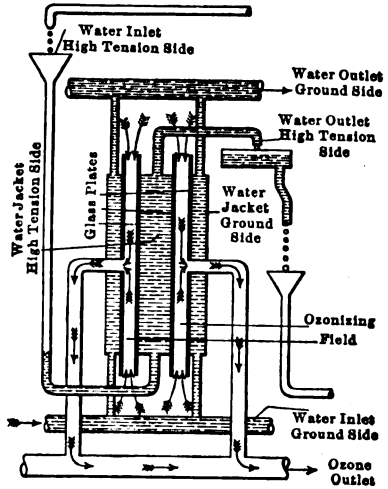


FIG. 29.—Plate ozonator.

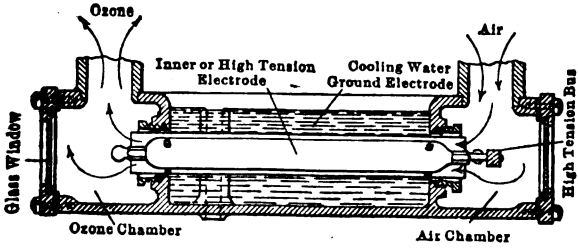


FIG. 30.—Tubular ozonator.

The advantages of the tubular ozoniser are compactness, relatively low voltage (about one-half that of the plate machine), readiness with which it may be assembled and taken apart, simplicity of the cooling system, and facility with which one or more units may be inserted or taken out.

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186. Concentrations and yields. For most industrial purposes the concentration should be in the neighborhood of from 1 to 3 g. per cubic meter of air, although in some special cases it may be as high as 5 g. It is rarely found expedient to operate at greater concentrations. The average yield is about 50 g. per kw-hr., and although much higher yields are claimed from time to time for certain types of generators these have not been attained in commercial operation.

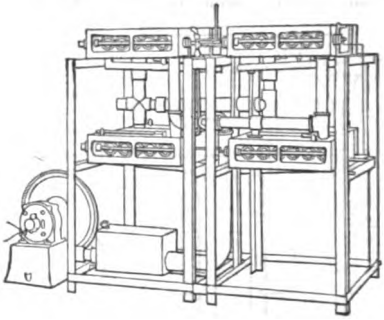


FIG. 31.—Tubular ozonator.

187. Oxidising effect of ozone. The applications of ozone are dependent upon the fact that it is a powerful oxidising agent and that it oxidises most substances at temperatures far below those at which they are capable of combining with ordinary oxygen.

188. Ventilation. Ozone is used in ventilation chiefly on account of its power of destroying organic odors. It has been shown that it is capable of oxidising the odors arising from various animal and industrial activities, for instance those of valerianic acid, butyric acid, skatol, indol, decayed foods, fish, tanners' scrap, manure, etc. The causes of distress in vitiated air are heat moisture and crowd odors. It is not believed that the organic excreta causing the latter are poisonous, although admittedly objectionable. Prof. Bass recently has conducted experiments on school children, which have established the fact that the addition of about one part of ozone in a million parts of air determines the difference between tolerable and intolerable conditions, when the air supply is very small.

189. Bactericidal power. It was at one time supposed that on account of the very great bactericidal power of ozone it would prove valuable in disinfecting the air of dwellings and factories, but it has been shown that in breathable concentrations it has little effect on the dry bacteria in the air; this, however, is immaterial, as it is now generally conceded that the dried bacteria in the air are not concerned in its vitiation nor in disease transmission. In suitable concentrations ozone may be used for disinfecting and deodorizing rooms that have become contaminated or infected.

190. Water purifications. The purification of potable water constitutes the most important application of ozone, in point of magnitude, up to the present time. The advantages of the method are the non-poisonous nature of the reagent; its insolubility which ensures against an excess remaining in the water; and the fact that besides rendering the water sterile it removes all taste and odor which might be due to organic defilement.

Water, to be ozonised, ordinarily requires filtering to remove the bulk of the organic matter, about 97 per cent. being thus eliminated. The ozone is relied upon to destroy the bacteria smell, taste and color which may persist after the filtering, which need be only roughly done. The ozone is introduced into the water under pressure and is caused to become intimately mixed with it by suitable mechanical means, such as agitation or forcing it through the interstices between broken rock or the like, or through sieves.

The cost of water purification by ozone is given by Erlwein as ranging from about $6.75 to $7.50 per million gallons, which includes all expenses such as interest and depreciation, and maintenance. The amount of ozone used ranges from about 2 g. to 15 g. per 1,000 gal.

191. The technical applications of ozone are very numerous and are increasing daily in number. Oils, fats, tallows and waxes may be bleached, deodorized, rendered tasteless and otherwise purified by means of ozone.

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192. Raw linseed oil may be converted into a good drying varnish by having ozone blown through it. At ordinary temperatures this results in bleaching of the oil and in increased viscosity. At elevated temperatures the oil darkens and it may be completely dried so as to be useful for the manufacture of linoleum. Raw menhaden oil may be clarified, deodorized, bleached and greatly thickened in the same manner. Raw cottonseed oil is bleached and deodorized besides being rendered viscous.

193. Ozone is successfully applied to bleaching cotton, linen and silk fabrics. It possesses great advantages over chlorine in that it is non-poisonous and need not be mixed in vats which suffuse the buildings with fumes. The use of ozone averts the necessity for handling, storing the bleach, and mixing the chlorine bleaching liquors.

194. Ozone is used successfully for drying oil varnishes, as in the manufacture of patent leather. If it is mixed with varnish, the latter dries quickly and evenly throughout its thickness, and if varnished surfaces are exposed to ozone it causes the formation of a protective surface while the underlying layers harden more slowly.

195. Ozone is applied to the cold-storage industry. For many substances there exists a critical temperature below which they may not be stored without danger of damage, and above which bacterial proliferation and other putrefactive causes result in deterioration. It is difficult to maintain these critical temperatures in rooms, the doors of which are being opened and shut constantly, and it has been found that with the aid of ozone all deleterious processes may be suppressed even though the temperature rises several degrees above the critical point.

196. In the brewery, ozone is becoming widely used. It is useful in sterilizing and drying the casks and in providing water of unsurpassable quality for the purpose of brewing. Recent researches have shown that it increases the power and activity of yeast.

197. Purification of sewage. It has been proposed to apply ozone to the purification of sewage, and while this is a subject of much experimentation, so far no instance of successful application has been recorded.

RADIOACTIVITY AND THE ELECTRON THEORY

BY EDWIN P. ADAMS, PH.D.

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RADIOACTIVITY

198. The radioactive elements are those whose atoms spontaneously break down, or disintegrate, with the expulsion of electrically charged particles; these particles are of two kinds, forming the α and β rays.

199. The β rays. These are made up of negatively charged particles, carrying the elementary charge: $e = 1.6 \times 10^{-20}$ expressed in absolute e.g.s. electromagnetic units. They are projected with velocities within a wide range of limits, some approaching within 1 per cent. of the velocity of light. The mass of these particles cannot be determined directly, but the ratio of the charge to the mass can be measured. The results show that the β particles from all radioactive substances are identical. According to the theory of a moving charged particle, its effective mass should increase with its velocity, but only appreciably when its velocity approaches that of light; a particle moving with the velocity of light would have an infinite mass. This prediction of theory is borne out by experimental results. The ratio of charge to mass for particles whose velocities do not exceed 3×10^{9} cm. per sec. is found to be 1.77×10^{7} in absolute c.g.s. electromagnetic units. Thus the mass of a single β particle is 10^{-27} grams. The β particle is the smallest known mass.

200. The α rays. These are formed of positively charged atoms of helium, carrying a charge double that of the elementary charge carried by the β particles. They are projected with definite velocities from the different radioactive substances, varying from 1.45×10^{9} to 2.22×10^{9} cm. per sec.

201. The γ rays. In addition to the α and β rays, which are formed of charged particles, radioactive substances also emit another type of radia-

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tion, the γ rays. According to theory, when a rapidly moving charged particle is accelerated, either positively or negatively, an electromagnetic pulse spreads out from it. It is probable that the γ rays are made up of a succession of these pulses, arising, mainly, from the sudden liberation and sudden stopping of the β particles. There is evidence that the α rays also produce γ rays.

202. The δ rays. When an α particle is ejected from an atom, the residue is negatively charged. It must move in a direction opposite to that of the α particle so that its momentum is equal to that of the particle. The δ rays are formed of the residues of the atoms after expulsion of α particles.

203. Effects produced by the rays. The α, β, and γ rays produce both photographic and ionising effects. To show the former effect, a photographic plate is exposed to a radioactive substance. It is found to be affected just as if it had been exposed to light. The ionising effects are shown by the rendering air a conductor of electricity. The neutral molecules of air are split into positive and negative ions through the action of the rays. When a potential difference is applied, these ions travel in opposite directions, thus setting up an electric current. The photographic effect is caused mainly by the β and γ rays and the ionising effect by the α rays.

The ionising effect is employed to measure the "activity" of a radioactive substance. Metallic uranium is taken as a standard, and by an activity of 100 times, is meant that the substance produces 100 times the effect of an equal weight of metallic uranium in rendering air a conductor of electricity under the same conditions.

204. Radioactive disintegration. The atoms of any radioactive element break down according to the law $N = Ne^{-\lambda t}$. N_0 is the number of atoms initially present, N the number after a time t has elapsed, and λ is a constant which has a definite value for each radioactive substance. External conditions are found to have no effect on the rate of disintegration. For example, the same value of λ is found whether it be measured at the temperature of liquid air or at the high temperature of an electric furnace. Thus radioactive disintegration is a phenomenon of an altogether different kind from any known chemical change.

205. Radioactive elements. Of the chemical elements that have long been known, only uranium and thorium have marked radioactive properties. There is considerable evidence that rubidium, potassium and sodium are also radioactive, but to a much less degree. In fact it is not improbable that all the elements are radioactive, the rate of disintegration of all but a few of them being too slow for detection. The phenomenon of radioactivity must be regarded as evidence of the instability of the atoms of the elements. The most unstable atoms are those belonging to the most radioactive elements. There is an enormous difference in the rate of disintegration of the different radioactive products. For example, uranium decays to half its initial amount in 5×10^9 years, while actinium A requires but 0.002 sec. for half of it to disappear.

There are three known series of radioactive elements, the uranium series, the thorium series, and the actinium series; it is not improbable that the last two series, as well as the first, have uranium as their parent. In each of these series, any member arises from the previous one by a radioactive disintegration, accompanied by the expulsion of an α or a β particle, resulting in the formation of an atom of a different kind. In the uranium series is found radium, the best known of the recently discovered intensely radioactive elements. There is some evidence that the final member of this series is lead.

206. Radioactive equilibrium. A series of radioactive elements is in equilibrium when just as much of any one of the intermediate products is formed in a certain time as disintegrates in the same time. In the uranium series, the constant λ of the disintegration of uranium itself has a value such that 5×10^9 years elapse before a given amount of uranium decays to half its initial value. Thus millions of years are necessary for the uranium series to come to equilibrium. In most uranium minerals the equilibrium condition is satisfied, so that there is a definite relation between the amounts of uranium and radium contained in them. It is found that the amount of radium associated with 1 g. uranium is 3.4×10^{-7} g.

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207. Heating effects. The continual emission of particles projected with high velocities from radioactive substances results in heating effects. The kinetic energy of the particle is transformed into heat. The α particles produce about 90 per cent. of the heating effect; while their velocities are lower than those of the β particles, their mass is so much greater that the kinetic energy of an α particle is many times greater than that of a β particle. One gram of radium in equilibrium with all of its products sets free approximately 118 cal. of heat per hr.

208. Radioactive minerals. The principal source of radium and the other strongly radioactive elements of the uranium and actinium series is the mineral pitchblende, which is an oxide of uranium. From this radium may be separated by chemical processes, its behavior being the same as that of barium from which it is separated by fractional crystallization. Carnotite is another uranium mineral, but of rarer occurrence. The principal source of the elements of the thorium series is monasite sand.

209. Uses of radium. Aside from its great scientific interest, the only important use of radium is as a therapeutic agent. Many cures of cancerous growths have been reported to result from its application.

210. Mesothorium, one of the members of the thorium series, is coming to be employed widely as a therapeutic agent. It has the advantage over radium of being easier to obtain. It is found in the residues left in the manufacture of thorium salts used in making Welsbach gas mantles. But it is far less permanent than radium. While 2,000 years must elapse for a given amount of radium to decay to half its amount, a given amount of mesothorium is reduced one-half in less than 6 years.

211. Determination of physical constants. The study of radioactive phenomena has resulted in the most reliable determination that we have of certain important physical constants. Some of these are given in the following table:

The elementary electric charge	$1.591\ 10^{-20}$ e.m. units
Number of molecules in 1 cu. cm. of a gas at 0 deg. cent. and 760 mm. of mercury pressure	$2.705\ 10^{19}$
Mass of the hydrogen atom	$1.662\ 10^{-24}$ g.
Ratio of the charge to the mass of an electron for small velocities	$1.767\ 10^{7}$ e.m. units

212. Bibliography.

RUTHERFORD.—"The Radioactive Substances and Their Radiations." New York, G. P. Putnam's Sons, 1914.

THE ELECTRON THEORY

213. The electron. The electron theory is built upon the observed wide distribution of electrons or corpuscles and their capability of accounting for many otherwise unexplained phenomena. Electrons are identical with the beta particles; the latter term is used to denote them when they appear accompanying radioactive disintegration. Electrons appear also under the name of cathode particles, when they are projected from the negative electrode, or cathode, by an electric discharge through a gas at low pressure. Ultra-violet light falling upon the surface of a metal sets electrons free; they are also liberated from incandescent solids. Whatever their origin, all electrons appear to be identical in nature. Their velocity of projection depends upon the circumstances under which they appear, but the ratio of their charge to their mass is the same for all except for the highest velocities of projection; this ratio diminishes with increase of velocity according to the same law in every case. The conclusion is forced upon us that the electron is one common constituent of all matter.

The model of an atom which has been most successful in accounting for many of the properties of matter is the Rutherford model. In this, the greater part of the mass of the atom is concentrated in positively charged nuclei whose size is small compared to that of the electrons, and the negatively charged electrons circulate about the nuclei in orbital motion.

214. Interpretation of electric phenomena in terms of the electron theory. In a conductor, in addition to the electrons contained in the atoms, which, in part, form the atoms, it is assumed that there are free electrons which pursue zigzag paths among the atoms. When the conductor is all at

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one potential there is no more tendency for these free electrons to travel in one direction than in any other. But when a difference of potential is applied to the conductor there is a force acting on the electrons driving them in a direction opposite the force, since they are negatively charged. Thus there is a drift of electrons in one direction, and this drift constitutes the electric current. An electric current, therefore, is to be regarded as a flow of electrons. In a perfect insulator, there are no free electrons but only those contained in the atoms. Thus there can be no continuous flow of electrons, *i.e.*, an electric current, in an insulator, under a constant electric force. When an electric field is applied to an insulator, the electrons inside the atoms move from their normal equilibrium positions until the forces of the external electric field balance the forces on the electrons arising from the atoms. There is thus a momentary flow of electrons inside the atoms and this constitutes the displacement or dielectric current. The displacement of the electrons from their normal position inside the atoms under the influence of an external electric force constitutes the polarisation of the insulator.

215. Thermoelectric effects. The free electrons inside a conductor may be considered as moving about exactly as the molecules of a gas. They thus exert a pressure corresponding to the pressure of a gas on its enclosure. This electronic pressure varies for different metals so that if two different metals are in contact there will be a greater pressure of electrons on one side of the junction than on the other. Suppose now that we have a closed circuit consisting of two different metals, with, therefore, two junctions. Let the two junctions be at different temperatures. As in the case of gas pressure, the higher the temperature the greater the pressure. So there will be a greater pressure driving the electrons from, say, metal A to metal B at junction 1, than from A to B at junction 2. There will thus be a steady flow of electrons around the circuit, constituting the thermoelectric current.

216. Magnetic effects on the electric current. An electron in motion constitutes an element of an electric current. So that if a magnetic field is applied, there will be a force acting on the electrons in a direction perpendicular to both the direction of motion of the electron and the magnetic field, and proportional to the sine of the angle between them. Suppose now that in a metal plate there is an electric current from left to right, and therefore a flow of electrons from right to left. Let the plate be placed in a uniform magnetic field perpendicular to it, the electrons will then be acted upon by forces in a direction perpendicular to their motion, and they will therefore traverse shorter distances measured in the direction of their drift between collisions with the atoms of the metal, and thus the resistance of the metal will apparently be increased. This effect, which is observed in all metals, is especially marked in bismuth, and is made use of in measuring magnetic fields; the increase of resistance of bismuth is a measure of the strength of a magnetic field.

217. Hall effect. If, in the case just considered (Par. 216), the ends of a wire be joined to two points at the ends of a line on the plate, which line is perpendicular to the direction of the current, a current will flow through this branch circuit when the magnetic field is applied. This is the "Hall effect," and may be explained by the bending of the paths of the electrons by the magnetic field which drives them through the branch circuit. According to this view, the Hall effect should have the same sign for all metals, i.e., with the primary current kept in the same direction and the magnetic field in the same direction, the secondary current through the branch circuit should flow in the same direction whatever metal is used. This is found, however, not to be the case. It is probable that the assumptions made are of too simple a nature; that the more complicated structure of a metal must be considered which is itself affected by the magnetic field.

218. Magnetism. In order to account for the magnetic properties of bodies it has been found necessary to consider the electrons contained in the atoms. We may consider the atoms as containing electrons circulating in closed orbits. It is a fundamental theorem in electromagnetism that a small closed current is equivalent, as far as its external effects are concerned, to a magnetic particle perpendicular to the plane of the current. An electron circulating in a closed orbit is equivalent to a current flowing in a closed circuit. So that if each atom contains a single circulating electron, it will be itself a magnet, *i.e.*, it will have a resultant magnetic moment. But in a

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ecessary to suppose that the atoms contain many electrons, and so it may appen that the magnetic moments of the different circulating electrons will eutralise each other, in which case the atom will have no resultant magnetic oment. When this is the case, the theory shows that the effect of an exrnal magnetic field is to modify slightly the electronic orbits in such a way to make the atoms exhibit a diamagnetic property. On the other hand, ie magnetic moments of the different electrons may not neutralize themlves so that the atoms have a resultant magnetic moment. In this case ie atoms show a paramagnetic property. The effect of the external magtic field is to orient the atoms in the same sense, and the substance as a hole becomes magnetized.

219. Electrons in optical theory. The electron theory has had its eatest success in the field of spectroscopy. The earlier applications of the ectron theory to optical phenomena proceeded from the assumption that electron in orbital motion inside an atom acted as a generator for electroagnetic waves; the frequency of vibration calculated on this assumption as of the order of magnitude of the frequencies of light waves. In recent ears Bohr's theory of the origin of spectral lines has received strong conrmation. According to this theory there are certain stationary states of otion of the electrons in an atom: in these stationary states no radiation energy takes place. In passing from one stationary state to another of ss energy radiation is emitted whose frequency, ν, is given by

$$h\nu = E' - E'' \qquad (6)$$

here E' and E'' are the energies in the initial and final states, and h is the niversal constant which enters into Planck's radiation formula. It is only r the atoms of the simplest constitution that this theory has been worked it in detail. In these cases it has been remarkably successful in accounting r the series of spectral lines; for the influence of a magnetic field in resolving ie lines into components (Zeeman Effect); and for the influence of an elecic field in causing resolution of the lines (Stark Effect).

220. Bibliography. Lorentz: "The Theory of Electrons;" Leipsic, G. Teubner, 1904.

Richardson: "The Electron Theory of Matter;" New York, G. P. Putam's Sons, 1914.

ROENTGEN RAYS

BY EUGENE W. CALDWELL, M.D.*
REVISED BY J. S. SHEARER, PH.D.

221. Discovery. In December, 1895, William Conrad Roentgen, then rofessor of Physics at the University of Wurtsburg, announced that while xperimenting with the vacuum tubes of Lenard, he had discovered a new rm of radiation which he called X-ray, because its exact nature was nknown.

222. Properties. These rays differ from the cathode rays previously scovered by Lenard in having greater penetration and in not being deflected y magnets.

Roentgen found that these rays would pass through materials opaque to rdinary light and set up fluorescence in crystals of barium platinum cyanide. e found that they could not be sensibly refracted or reflected by any materals available; that they were not deflected by a magnetic field; that they enetrated different materials in a ratio approximately inversely proportional the atomic weights, and that they acted like light on the silver salts used photography.

223. The transparency of materials to X-rays depends on the atomic eight and on the voltage used in operating the tube. Taking water as andard of comparison aluminum will transmit about 38 per cent. as much an equal thickness of water for radiation from tube operation at medium orking voltage. Copper would transmit about 8 per cent. as much as ater.

224. Scattered rays. A small proportion of an X-ray beam is scattered y the material through which it passes. These scattered rays are not anged in wave length or quality.

* Deceased.

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225. Characteristic rays. J. J. Thompson has shown that when X-rays strike metallic plates such as copper, silver, lead, etc., new rays are set up at the metal surfaces, having penetrating properties peculiar to the metal from which they arise and independent of the penetration of the rays producing them. The tube voltage used must not be below a certain value peculiar to each metal. This voltage increases with atomic numbers.

226. Theory. The discovery of Laue that a crystal acts as a three-dimensional diffraction grating proved that X-rays are identical in nature with light radiant heat, etc. The average wave length is about one ten-thousandth that of waves in the visible spectrum.

227. Conditions necessary for production. When an electrical discharge is passed through a vacuum tube exhausted to a Crookes vacuum (much higher degree of exhaustion than in the tubes of Hittorf, Geissler and Lenard) X-rays are produced wherever the cathode stream is arrested by the walls of the tube or metallic objects therein.

228. Cathode rays or electrons. X-rays are originated by the sudden change in velocity of small electric charges on impact matter. These charges are elementary units of negative electric charge and are now generally named electrons.

229. Quality and penetration of X-rays. The quality of an X-ray beam is related to the various wave lengths involved just as the quality of sound is governed by the loudness and pitch of each constituent tone heard. When a tube is operated at 25 kv. the wave lengths will range from about 0.48×10^{-8} cm. to 0.8×10^{-8} cm. Raising the operating voltage will change the radiation as follows:

(*a*) Increase the energy of all wave lengths present at the lower voltage.
(*b*) Introduce shorter waves than were present at the lower voltage.
(*c*) Shift the region of maximum intensity toward the shorter wave lengths.

The absorption for a given thickness of absorber increases very nearly as the cube of the wave length. It follows that the fraction of the original beam passing through a given thickness of material depends on the composition of the beam, consequently the penetration will change with the operating voltage. Since on increased voltage there are introduced shorter wave lengths the beam is made more penetrating by higher voltage operation.

230. X-ray tubes. There are two types of tube in use at present. The earlier type contains a limited amount of gas from which the supply of electrons is obtained. This may be designated briefly as the gas tube. In the more recent type developed by Coolidge the electrons are freed by heat from a wire (the filament) and it is spoken of as the **hot cathode tube**. In all tubes designed for radiographic or fluoroscopic work the cathode must be so designed as to concentrate the electron stream on a very small area or focal spot.

231. Characteristics of tubes. The quality of radiation from a tube depends slightly on the nature of the target or anode, but mainly on the operating potential. The amount of radiation will depend on these and on the amount of current. When tubes of the same target material are operated at the same current and voltage they develop the same quantities of radiation of the same quality.

Control is secured by regulation of current and voltage. One may increase the applied voltage or alter the internal condition of the tube or both. Applying increased voltage to a gas tube will cause increased current and may or may not result in increased operating voltage. Also its behavior is largely dependent on the amount of free gas in the bulb and this needs control. Various ingenious devices have been developed for this purpose. In the hot cathode tube the amount of negative charge freed from the hot cathode fixes the maximum current possible, and varies with the temperature of the filament. Control is secured by variation of filament current and of the applied voltage operating the tube.

232. Generating apparatus. The voltages required for tube operation vary from 30 k.v. to approximately 90 k.v. The current varies from 2 to 75 or 100 milliamperes. Such high voltages require transformers for their production. When direct currents were mainly used, the induction coil with interrupter was in general use. In the United States this has been almost entirely superceded by the alternating-current transformer. This

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must be connected to a suitable revolving switch or rectifier for use with gas tubes or high power Coolidge tubes. For operation up to 30 milliamperes at 60 k. v. a Coolidge tube has been perfected that may be connected directly to the transformer. Such tubes are as yet unsuitable for continuous operation above 3 milliamperes.

233. Measurement. It is customary to measure the current passing through the tube, with an ordinary milliampere meter of d'Arsonval type mounted on an insulating support and having one terminal connected to the metal case. The potential difference across tube terminals is estimated by length of equivalent spark gap. Electrostatic voltmeters may be used for this purpose.

The *quality* of the ray is best expressed by giving the true equivalent spark gap since voltage is the factor fixing quality or penetration.

The measurement of quantity of X-ray is usually made by comparing, with a standard scale, the change in color produced in a chemical test piece which has been exposed to the rays.* Stern in 1903 proposed to use strips of bromide paper for measuring the dose of X-ray; the strips were developed, after exposure, for a standard time in a standard developer and then compared with a color scale. The Kienboeck quantimeter which appeared a few years later is essentially the same device. Sabarand and Noiré use discs coated with barium platinum cyanide which turns darker when exposed to X-rays.

There is a growing tendency to replace empirical measures of this class by a statement of current, spark gap, distance and time in order to estimate the amount of radiation received by an exposed surface. For laboratory purposes the ionising power of X-rays is used as a measure.

234. X-ray spectra. By means of the diffracting power of crystals the distribution of energy among the various wave lengths has been measured as well as the actual wave lengths. Knowing wave lengths the spacing and types of arrangement of atoms in crystals have been studied.

235. Principal uses. The medical and surgical use of X-rays in diagnosis and therapy are still the most important, but recently many new fields have developed, such as inspection of materials, chemical analysis, study of crystals, detection of flaws in manufactured products, etc.

236. Roentgenography. The so-called X-ray photography for medical or surgical diagnosis should not be undertaken by electricians or photographers. The safe interpretation of Roentgen ray shadows is difficult, and requires special training. Their resemblance to photographs makes them misleading to the inexperienced.

237. X-ray burns. The so-called X-ray burns may be acute, *i.e.*, developed from a single prolonged exposure, or they may be chronic, developing gradually as a result of repeated small exposures which, individually, would produce no noticeable effect. The acute burn seldom appears before five days after the exposure and sometimes as late as three or four weeks later. The reddening, blistering and sloughing observed in ordinary burns and due to death of tissue, are present. All X-ray injuries are especially slow in healing. The chronic type resembles the senile keratosis (the horny skin produced by the sun and wind on the faces and hands of old people). These chronic keratoses are classed as precancerous, and when once established are prone to increase and develop into cancerous growths without further exposure.

In the ordinary application of the ray for diagnosis or treatment the danger to the subject is little, but physicians working daily around X-ray tubes must observe caution to escape injury.

To protect the patient, screens of aluminum from ½ to 3 mm. thick are interposed to cut out the rays of low penetration which would otherwise be absorbed by the skin.

The tubes are shielded by being enclosed in chambers composed of metal or lead glass.

The controlling devices are placed behind screens of lead from 2 to 5 mm. thick and provided with lead-glass windows. Protective aprons and gloves, composed of rubber cloth impregnated with lead or bismuth salts are worn by the operator.

* S. Stern, *Journal of Cutaneous Diseases*, Dec. 26, 1907.

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238. Treatment of injuries. The treatment of X-ray injuries is very difficult and tedious. Surgical removal with skin graft may be necessary. It is extremely important to avoid the use of irritating or stimulating ointments such as the much advertised skin remedies.

The chronic keratoses may be destroyed by freezing with liquid air or carbon dioxid snow, by burning with high-frequency sparks, or by exposure to the rays of radium. These agents all produce a destruction of tissue following by sloughing. Of these, radium is by far the least painful.

239. Literature. The literature on X-rays is mainly to be found in conjunction with works on its medical applications. In addition there is a growing periodical literature in technical magazines on the commercial applications. Brief scientific works are: "X-rays," Kaye; "X-rays," General Electric Company; "X-rays and Crystal Structure," Bragg; The "U. S. Army X-ray Manual," gives a general idea of this field.

LIGHTNING RODS

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240. Source of atmospheric electricity. Among the many theories propounded that of Dr. George C. Simpson* appears perhaps most rational. In brief he concludes from laboratory experiments with drops of water in air that when such drops are broken up in smaller drops the water becomes positively and the air negatively charged. This fact used in conjunction with Lenards proof that drops larger than 0.2 in diameter are unstable when falling through air and that drops smaller than 0.2 in diameter attain a velocity less than 18 miles per hr., form the basis for the following brief explanation quoted in Dr. Simpson's words.

"It is exceedingly probable that in all thunderstorms ascending currents greater than 18 miles an hour occur. Such currents are the source of large amounts of water which cannot fall through ascending air. Hence at the top of the current, where the vertical velocity is reduced on account of the lateral motion of the air, there will be an accumulation of water. This water will be in the form of drops which are continually going through the process of growing from small drops into drops large enough to be broken. Every time a drop breaks a separation of electricity takes place, the water receives a positive charge, and the air a corresponding amount of negative ions. The air carries away the negative ions, but leaves the positively charged water behind.

"A given mass of water may be broken up many times before it falls, and in consequence may obtain a high positive charge. When this water finally reaches the ground it is recognised as positively charged rain. The ions which travel along with the air are rapidly absorbed by the cloud particles and in time the cloud itself may become highly charged with negative electricity. Now, within a highly electrified cloud there must be a rapid combination of the water drops, and from it considerable rain will fall; this rain will be negatively charged, and under suitable conditions both the charges on the rain and the rate of the rainfall will be large.

"A rough quantitative analysis shows that the order of magnitude of the electrical separation which accompanies the breaking of a drop is sufficient to account for the electrical effects observed in the most violent thunderstorms. All the results of the observations of the electricity of rain described above are capable of explanation by theory, which also agrees well with the actual meteorological phenomena observed during thunderstorms."

241. Importance of lightning protection. Statistics show that in this country, between 700 and 800 persons are annually killed by lightning and about twice as many seriously injured.† The efficiency of lightning rods for farm houses in the middle west can be judged from statistics gathered by Mr. E. W. Kellog‡ who concludes that for an equal number of houses

* Proceedings of the Royal Society, Series A, Vol. LXXXII, p. 169.

† Farmers' Bulletin, No. 367, U. S. Dept. of Agriculture.

‡ University of Missouri, Bulletin No. 7, Eng. Exp. Station.

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rodded and not rodded, the fires due to lightning are approximately 15 times greater with the buildings not rodded than with those which are rodded.

242. Nature of the discharge. Sir Oliver Lodge first suggested that there are at least two distinct kinds of discharges, one of which is relatively quiet and which results from the gradual breaking down of the air between the object struck and the charged cloud and another which is a violent secondary discharge caused by a primary discharge in the vicinity.* The first kind follows the well-known laws familiar to the electrical engineers—laws that deal with more or less permanent conditions. The nature of the discharge is governed by the resistance, inductance and capacity of the path. The path itself is almost certain to be the rod on account of the conducting streamers above it. The second kind is more complex, and the laws that it follows are less thoroughly understood. There is no conducting path above the rods because there may have been no potential difference between them and the surrounding air before the discharge. Thus the rods may readily be missed, and the discharge may enter any portion of the roof and find its way to the ground through the building. To guard against these contingencies it would seem that the entire roof should be of metal, or at least largely covered by metal network.

Prof. Flemming has compared the first with the slow combustion of gun powder placed in a room and carefully lighted, the second with detonating powder. In the first case the heated air and gases of combustion are readily guided through the chimney and do no harm; in the second case no matter how large the chimney is, enormous pressures will exist in all directions. The reason for this is that, while the inertia of the air normally is very small and it can readily be displaced, it becomes tremendous when sudden forces are applied; in fact, during the very first instant the air acts as a solid.

243. Electrical constants of lightning rods. While the number of oscillations of a lightning discharge in clouds or between clouds and earth is entirely unknown and may perhaps even be zero, it seems necessary that the discharge originating in the vicinity of the rod and carried in the rod must be of very high frequency. In the passing of high frequency currents, energy is expended as heat at the surface of the conductor and as electric radiations in the surrounding space. The ohmic resistance, which depends upon the conductivity and the cross-section of the rod, is of practically no importance; even the shape of the conductor, which is of much importance with frequencies from 100 to 100,000 cycles, possesses relatively little importance at still higher frequencies.

The same applies to the inductance of the conductor—it is also practicably independent of the kind of material or its cross-section. It is evident that, provided the lightning discharge in the rod is a high-frequency oscillation, from an electrical point of view it matters really very little whether copper or iron, flat or round, stranded or solid conductors are used, although there is a slight advantage in flat ribbons at all but the highest frequencies. The object of the lightning rod is to present a path for the discharge, a path offering much less obstruction than any path through the building. If the ohmic resistance were all important this could well be done by using a very large copper rod, but at these very high frequencies the obstruction or impedance as measured in tens or even hundreds of ohms, whereas the ohmic resistance may be but a small fraction of an ohm.

244. Electrical characteristics of lightning itself. The greatest number of lightning discharges take place inside clouds or between adjacent clouds. These discharges involve usually rather moderate voltages, and while interesting are hardly within the scope of this paper. The knowledge of the nature of lightning discharges from cloud to earth is, however, of greatest importance in studying the efficiency of lightning rods. Unquestionably such discharges take place not only at moderate voltages, but also at voltages which are exceedingly high; the latter being true when the charged cloud is separated from earth by a layer of more or less dry free air.

Under these extreme conditions the distribution of potential may be fairly uniform, and the air may be charged to its breakdown point all through its mass, in which event the potential difference would be exceedingly great. The maximum value of the discharge current may also be very great, reach-

* Lightning Conduction, published by Whittaker & Co.

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ing several thousand if not hundreds of thousands of amperes, as may be judged from the consideration of the following simple case. An area on the surface of the earth 100 ft. square is subjected to the discharge of a cloud also 100 ft. square, at a distance of 1,000 ft. In this case the capacity is approximately 0.000027 microfarads, a very small capacity indeed, something like that of the smallest Leyden jar. If the electric stress as assumed were uniformally distributed throughout the air space separating cloud and earth, and if the disruptive strength of air is 30,000 volts per cm., a potential of 912,000,000 volts would exist between cloud and earth just before the stroke. The electric charge, that is, the amount of electricity stored, would be 0.025 coulombs, a very small value when considered by itself. The energy stored would, however, be great on account of the high difference of potential. It would be 11,200 kw-secs., corresponding to the energy of almost a pound of dynamite. This energy is expended in heat and electric radiation, partly in the stroke before it reaches the rod, partly in the circuit of the rod. The higher the frequency the greater is the relative amount radiated. With a small copper rod the energy radiated at 1,000,000 cycles is perhaps 50 times as great as that converted to heat in the rod. Whether, however, the energy is radiated or directly converted to heat is not so material. In either case the maximum current in the rod may be enormous and depends upon the frequency of the discharge. With a lightning discharge this may be from 100,000 to perhaps 5,000,000 per sec., in which case the maximum value of the current is from 15,000 to 750,000 amp., it being proportional to the frequency. Steinmetz* has shown that the impedance or total obstruction of the high frequency conductor is about 0.1 ohm per ft. at 100,000 cycles, 0.5 ohm per ft. at 500,000 cycles, 1 ohm per ft. at 1,000,000 cycles, and 2.5 ohms per ft. at 5,000,000 cycles. Thus the maximum drop of potential per ft. of lightning rod would be 1,500 volts at 100,000 cycles, 9,000 volts at 250,000 cycles, 37,000 volts at 500,000 cycles 150,000 volts at 1,000,000 cycles and 1,880,000 volts at 5,000,000 cycles.

245. Relation of frequency to other factors. While in every discharge almost an infinite number of frequencies undoubtedly are represented, it is probable that one is preponderating. Were it permissible to consider that the frequency in the discharge after it reaches the rod is governed only by the electrical constants of the rod, the wave length would be somewhat more than four times the height of the rod. This would mean with an ordinary dwelling with a rod of say about 50 ft., about 5,000,000 cycles. If on the other hand the effect of the rod is hardly noticeable and the frequency is governed by the distance between cloud and earth, the frequency will be much lower, say 250,000 cycles, with a distance of 2,000 ft. between the cloud and earth.

In the first case the drop in potential per ft. is about 2,000,000 volts, in the second case only 9,000 volts. The first case gives an idea of the conditions of a secondary stroke. It is of very high frequency and may be the result of the discharge of the air immediately surrounding the rod rather than the entire air between cloud and earth. The discharge area is in this case difficult to estimate; it may be quite limited or it may be quite great.

Assuming again an area of 100 ft. square and calculating the voltage and capacity, it is found that the capacity is increased in the same proportion as the voltage is decreased; therefore the charge and maximum vale of the current remains unchanged. The maximum value of the current would be, as 750,000 amp., and the drop per ft. of rod about 2,000,000 volts.

It is evident that only a very small part of such discharge would travel through the conductor, and that the main discharge would jump several feet in the air rather than travel 1 ft. in the conductor. (The drop in potential of 2,000,000 volts per ft. corresponds to 2 ft. striking distance between parallel planes and perhaps 10 ft. distance between projecting masses of metal.)

The second case is approached when a lightning discharge takes place from cloud to rod after a conducting path has been prepared by means of streamers. It is the first, the quiet type of lightning mentioned in the beginning of the paper.

246. Advantage of multiplicity of rod. A single lightning rod may be expected to take care of low frequency discharge from cloud to earth, but is entirely inadequate to cope with a violent secondary discharge, even if it struck the rod instead of the building proper.

* "Transient Phenomena." McGraw-Hill Book Company, Inc.

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)ne lightning rod, while offering some protection, may be considered, under ıormal conditions, entirely inadequate to cope with the situation. If the ldings were grounded by ten rods the condition would be much improved, l the lightning discharge would probably be confined to the system of rods.

247. Installations. Experience seems to have settled beyond reasonable ıbt, that, if properly installed, lightning rods afford considerable pro- tion. A large number of instances might be quoted, but suffice it here to ntion only one. Before equipping the buildings of The University of nois with rods, three fires were caused by lightning; since that time, though number of buildings has been greatly increased, there has been no damage m lightning. It should be remembered, however, that a rod faultily talled may make matters worse than would be found where no rods were ıd. Assume, for instance, that a large building is equipped with a high t broken rod having poor joints or a high resistance to ground, say several ndred ohms, which undoubtedly sometimes is the case. Such a rod could ve the function of equalizing the potential between cloud and earth almost effectively as a good rod, and were there only a sufficient number of them ıs conceivable that the neutralization of potential would be so complete to make a flash discharge practically impossible. A building having one l only, however, is considered at present. The rod is assumed as project- considerably above the building. If the electric tension is great, un- estionably streamers are emitted, the air above the rod is made fairly nductive and thus the discharge is invited. The question is then: How n such a rod take care of the discharge? It has been shown how the dis- arge current frequently is very large and while the ohmic resistance of e rod is practically immaterial as long as it is at all reasonable, it must t approach or exceed the normal value of the impedance. In a rod, say ft. long, the ohmic resistance of even the smallest practicable iron conductor a fraction of an ohm only and the impedance is perhaps 30 to 75 ohms, pending upon the height and frequency of the discharge. It is easily en that a poor joint may have many times this resistance; therefore, when e discharge encouraged by the streamers from the defective rod strikes the ilding it finds the rod entirely inadequate to cope with the situation. The ltage drop in the rod is so great that it is far easier for the current to split in a number of paths and enter through the building than to confine itself the rod. An apparent paradox thus exists. The rod should have good ints, should have good ground connection, and should be mechanically cure against breaking; although the shape of the rod, its metal or its general mensions are rather immaterial.

248. Location. The rods should always be placed outside of the building ıd it is indeed a question whether the vertical part of the system, that is, ıe rod proper, should not be some little distance from the wall and possibly 'en insulated therefrom. They should be placed a considerable distance om gas pipes, stove pipes, water pipes and balconies or places where persons ight be during a storm.

249. Material and construction. Lodge's experiments and theory ıow conclusively that there is no advantage in copper over iron. Copper ay have mechanical advantages under certain conditions, for instance in ties where the atmosphere is charged with soot and a variety of fumes. alvanised iron has the advantage of cheapness, with a possible electrical ıperiority. While flat conductors have a very slight advantage, it appears o small to be considered seriously. A round wire or a pipe can be handled ınveniently, and seems preferable. In the installation of the rods, sharp ınds should be avoided as much as possible. There is little or no advantage using large and expensive copper conductors or cables; a size mechanically tisfactory is likely to serve all electrical purposes. Expensive sharp points fer little advantage over ordinary rather blunt points. The rods may lvantageously terminate in a number of points projecting only a short stance above the part to be protected.

250. The ground connection should be of low resistance, and therefore ıe rods should preferably terminate in moist soil. "Salting" the ground ay be an advantage, but experience with such grounds is not sufficient to arrant its adoption unless an occasional inspection is made. In many cases ıcellent connection can be made by driving a galvanized gas pipe a few et into the ground. In installing the rod, allowance for expansion and con-

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traction should be made. Gas pipes should not be connected to lightning rods, nor should the rods be placed in too close proximity to them.

251. Precautions. A building having its windows and doors open affords opportunity for the entrance of air, perhaps ionized air made conductive by a previous discharge. It is, therefore, safer to keep the house closed during a violent storm. It is also well to keep away not only from the rod but from chimneys, kitchen ranges, metal pipes, etc.

The damage by lightning in cities is relatively small, and so far the modern sky scraper, with its vast amount of steel, appears to be lightning proof.

ELECTROSTATIC MACHINES

BY OTIS ALLEN KENYON

Engineer, Roy D. Lethbridge, Inc., Member, American Institute Electrical Engineers, Member Society Automotive Engineers

252. Classification. There are two fundamental types of electrostatic generators, namely, those in which the e.m.f. is generated by contact of two unlike substances and those in which it is generated by electric induction; the former are called frictional machines and the latter are called influence machines.

253. Frictional machines. In a circuit composed of unlike materials there exists a difference of electric potential at the junction of these materials. However, from the law of the conservation of energy, no electricity will flow in the circuit unless energy from an external source is applied thereto. In frictional machines the energy which produces the flow of electricity is supplied by the heat due to mechanical friction.

254. Electrical Series* (Riess)

Positive	Negative
Fur, human hair	Glass, porcelain, wood, metals, rosin, sulphur.
Glass	Zinc—tin amalgam on leather (sure).
Fur, wool, linen, silk, paper, metals	Rosin, sealing wax, sulphur, shellac, amber (sure).
Diamond, topaz, thummer-stone, quarts, calcareous spar, mica, polished glass.	Wool, linen, silk, leather.
Glass, silk	Metals.

255. Theory of frictional machines. When two unlike bodies are rubbed together, the energy applied is partly stored by the establishment of a dielectric field and partly dissipated as radiated heat. The dielectric

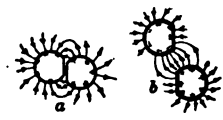


FIG. 32.

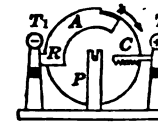


FIG. 33.

field established while the two bodies are in contact causes electricity to flow to the surface of the bodies, a positive charge being collected at one extremity and a negative charge at the other. The energy thus stored, in watt-seconds, is numerically equal to the product of the strength of the dielectric field in volts, and the quantity of electricity transferred, in coulombs. The energy

* The substances at the left are each supposed to be rubbed with any one of the substances given at the right and in the same row.

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us imparted to the dielectric field may be manipulated so as to raise the m.f. to a point limited only by the dimensions and insulation of the machine. or instance, in the case of two bodies in contact as at a, Fig. 32, the quantity electricity transferred by the dielectric field is $Q = CE$ and the energy us absorbed is $W = EQ$ where Q is the quantity in coulombs, C is the pacity in farads, E is the potential difference in volts and W is the energy joules. If the two bodies are separated as at b, Fig. 32, the capacity is duced to C', and since the quantity Q is fixed, the strength of the dielectric ld must increase to E' in accordance with the relation $E' = Q/C'$. However, $Q = W'$ is greater than W; therefore, it requires mechanical force to separate e bodies.

256. Construction of a laboratory type of friction machine is shown Fig. 33. A glass plate, P, is rotated in the direction shown by the arrow id the rubbing surface, R, which is made of leather coated with an amalgam good amalgam recommended by Kienmayer is 1SN + 1Zn + 2Hg), rubs ainst the glass plate generating a dielectric field which conveys the negative ectricity toward the terminal T_1 and the positive electricity to the opposite de of plate P. At the comb C the dielectric flux is so dense that the air is ndered conducting and electricity passes between P and T_2. Thus the ndency is for positive electricity to be transferred to T_2 and the negative ectricity to T_1. The energy for this transfer of electricity is generated by e friction between R and P, and the potential of the machine depends upon s own dimensions and its insulation.

257. Experiments by Reiss* disclose the relation between e.m.f. nd friction. The results are given briefly as follows: a flat metallic linder, 1.575 in. (40 mm.) in diameter, covered with leather, was set upon ebonite plate and drawn by an insulated handle over the surface, the harge being measured with a sine electrometer. The disc was drawn 1.18 . (3 cm.) in one place; it was then set in another place and drawn 1.18 in. cm.) again and so on, eight times, with the following results:

Number.....	1	2	4	8
Charge.....	1	1.45	1.7	1.93

Next the disc was drawn 9.45 in. (24 cm.) without stopping and the same sult (1.93) was obtained. It was also found that there was maximum alue beyond which the charge was not increased by drawing the disc rther.

258. Influence machines. The second type of machine, based on the rinciple of electric induction, and commonly known as the influence machine, perates as follows: a conductor thrust into a field of dielectric flux will have a e.m.f. generated in it hich will cause a certain uantity of electricity to ow, and store a corre-ponding amount of energy. ig. 34 shows two bodies, and 2, connected to a attery B as a source of m.f. The e.m.f. estab-shes a dielectric field be-ween the bodies, drawing nergy from the battery nd storing it in the elec-ic circuit. The energy tored is $W = C(E/2)$, herein C is the capacity, nd E the e.m.f. of the attery. Now if two odies, 3 and 4, connected conductively, are inserted into the dielectric eld, the capacity C, which is inversely proportional to the length of the di-ectric will be increased, and the value of the dielectric flux correspondingly

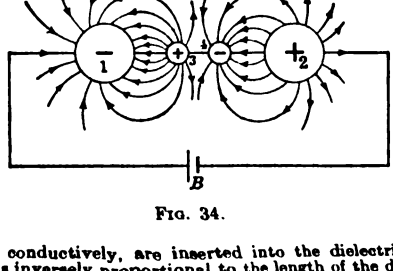


FIG. 34.

* "Wiedemann Annalen," Bd. I, p. 1052.

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increased, thus drawing more energy from the battery and storing it in the system. Electromotive force will be generated in the bodies 3 and 4 which will tend to start a flow of electricity, and will transfer a quantity of electricity to the outside surface of the plates, sufficient to absorb the increase of energy stored in the system. If while in this position the two bodies are separated by severing the connecting link, the electricity will be unable to return to its state of equilibrium and the energy stored will remain bound. In order to utilise this energy, the bodies must be removed from the electric field of 1 and 2, and, now that each has a field of its own, mechanical energy equal in value to that stored in the bodies will be required to remove them. When the bodies are removed, the capacity of 1 and 2 will return to its original value, and the extra energy called forth for the placing of 3 and 4 in the field will be returned to the battery.

259. Excitation of influence machines. The influence machine does not employ a battery to maintain the e.m.f., but is given an initial charge of e.m.f., after which it is self-exciting. It will be noted that in this method a certain amount of electricity is stored in the bodies 3 and 4, and that the value of e.m.f., and therewith the value of the energy can be changed at will by varying the capacity between them; an increase in capacity corresponds to a decrease in energy or motor action and *vice versa*.

260. The Toepler influence machine is shown schematically in Fig. 35. *S* is a fixed glass plate with two segment-shaped pieces of paper, p_1 and p_2 (called field pieces) fastened on the back (shown dotted); *P* is a glass plate mounted on an axle and can be rotated by a belt not shown in the sketch; on the plate, *P*, are mounted a number (8 in the sketch) of tin-foil discs called carriers, each disc being armed with a small brass button which makes the contact with the various brushes; b_1 and b_2 are called appropriately brushes and are connected with the field plates p_1 and p_2, respectively. *n* is the neutralising rod and carries a brush at each extremity; c_1 and c_2 are metallic combs connected to the terminals, T_1 and T_2, of the machine. The Toepler machine is very reliable and is self-exciting regardless of weather conditions. By connecting a number of pairs of plates in multiple the load capacity of the machine can be increased.

261. The polarity of the Toepler type of machine is not always the same, depending on how the charges are distributed when it starts. Tests for polarity should be made, where it is of importance. The flame of a Bunsen burner will be attracted by the negative pole.



FIG. 35.

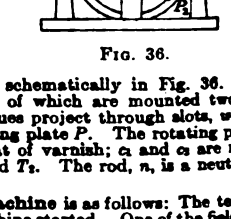


FIG. 36.

262. The Holtz machine is shown schematically in Fig. 36. *S* is a stationary glass plate on the back side of which are mounted two paper field plates, P_1 and P_2; small blunt tongues project through slots, *w*, in the glass plate *S* and nearly touch the rotating plate *P*. The rotating plate, *P*, is a plain glass plate covered with a coat of varnish; c_1 and c_2 are metallic combs connected to the terminals, T_1 and T_2. The rod, *n*, is a neutralising rod and carries a comb at each end.

263. The operation of the Holtz machine is as follows: The terminals T_1 and T_2, are put in contact and the machine started. One of the field plates is given a charge (let P_1 be charged positively). This charge will draw negative electricity to the comb, c_1, which will leak across to the glass plate *P*. Passing around to the other side of the machine this negative charge on plate *P* attracts a positive charge from the plate, P_2, to the other side

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› plate, leaving P_2 negative. Now the negative charge on P_2 draws positive otricity from c_2 which neutralises the negative charge and leaves both sides the plate negatively charged. Upon coming to the other side the positive charges on both sides of the plate draw negative electricity from the field ıte, P_1, neutralising the charge on the lower side of P and completing the cle. The neutraliser, n, serves to keep the machine from reversing its larity and losing its excitation.

The Holtz machine is sensitive to atmospheric conditions and should be closed in a tight compartment for satisfactory results. The compartment n be heated or some moisture-absorbing agent can be used to keep the air y. The polarity of the machine can be determined by observing the aracter of the sparks at each pole; at the negative pole the sparks between e comb and the plate are broad and occur in bunches giving a bluish light, ıile at the positive pole they appear as single points of light.

264. Effect of operation under air pressure. Influence machines n be greatly increased in e.m.f. by enclosing them in an air-tight case and ›erating them under air pressure. As discussed in Sec. 4, the dielectric rength of air is increased by raising the pressure, therefore higher e.m.fs. n be generated without causing the air to break down and neutralise the ıarges. Tests on an experimental machine* gave the following results:

ressure, lb. per sq. in.	0.0	15	30	45
›ark length, in.	2.5	5	7	8

ELECTRIC PIANO PLAYERS

BY OTIS ALLEN KENYON

ngineer, Ray D. Lillibridge, Inc., Member, American Institute Electrical Engineers, Member Society Automotive Engineers

265. The Tel-Electric piano player is the name that has been given to ıe of the most successful types of electromagnetic piano player that has been ›veloped. In this system the keys of the piano are operated by a bank of ectromagnets situated immediately beneath the keyboard, thus interfering no way with the usual manual operation of the instrument. The electric apulses which operate these magnets are produced in a separate apparatus ıat may be situated at any distance from the instrument that is to be played.

266. Operation. The Tel-Electric player is so designed as to operate ther automatically, or subject to manual control. In operation, a roll of ıusic is inserted in the carriage and the starting switch closed. Once started, ›e music roll, which is driven by a motor, is drawn through the transmitter, ›us actuating the playing magnets according to the pattern of the music ›eet. At the end of the selection, the roll is automatically reversed and ›ound back into its case and the current cut off.

267. The music roll consists of sheet brass into which a pattern has been unched. This roll forms the selective means which determines the sequence f the magnets that operate the keys and the pedals, and also the strength f the current through these magnets.

268. There are three general types of this player now on the market. he first is known as the "Tel-Electric," which is a sixty-five note player, and perates the keyboard of a piano from the second "A" in the base to the last C sharp" in the treble. The various degrees of expression are controlled by resistance bank, there being a resistor for each individual magnet. The **xpression control** device permits the required length of the resistor to be ıtroduced in each individual magnet-circuit, the changes in the amount of ›sistance being effected practically instantaneously. With this complete ›ntrol of each individual note and the pedals, the melodies and rhythms are layed with practically perfect expression.

The second type of player is denoted as the "Telelektra." It controls ighty-eight notes, or the entire keyboard of a piano, and produces even more erfect control of expression than does the Tel-Electric. With this player is possible to get as many degrees of expression as a piano virtuoso can

* Elmer and Amend.

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produce. Any variety of contrast between the melody and accompaniment is possible. In the Telelektra, the current for the operating magnets is varied, partly by the resistance method and partly by vibrating contacts, the rate of vibration being regulated by the music record. At zero vibration full current passes, and as the rate of vibration increases the value of current decreases in direct proportion to the time of contact. The contacts of the number of vibrations of these contacts is so perfect and so nearly instantaneous that a practically unlimited number of degrees of expression may be produced. The Tel-Electric players are operated by what is known as **autographic records**, made by a special process which permits the automatic recording of the note position and the power applied to the key for each individual note, as played by the person who produces the record.

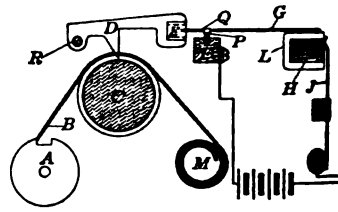


FIG. 37.—Skeleton diagram of the operating mechanism of a Tel-Electric piano player

The third type is known as the "Telektra Symphonic Organ," is simply an adaptation of the Telelektra to the **pipe-organ transmitter.** The organ is specially designed for the purpose, and though many sizes of organs are constructed, standard music rolls are made that can be played in all the various sizes. The player system is laid out to cover an organ of three claviers and thirty-two note pedal, 100 stops, all couplers and accessories, and three independent swell boxes. As there is no limit to the number of notes or combinations that can be put into operation simultaneously, the automatic player can produce effects that are impossible to the organist. The Tel-Electric system may also be applied to existing organs, and, in every case, the organs may be operated by hand in the usual way without removing the player.

269. Mechanism. The principle upon which the translating mechanism operates is shown in Fig. 37. The brass record, which is perforated with longitudinal slots, is wound from the roll *A* to the roll *M* over the so-called tracker roll *C*. Above the tracker roll there are arranged a number of reading fingers *D*, mounted on a shaft *R* about which they are free to rotate, there being a finger for each magnet on the piano, as well as for the expression magnets. These reading fingers each carry a contact wire *G* embedded in a piece of ivory *E*. Normally the reading fingers rest upon the surface of the brass record and the circuit of the magnet is open

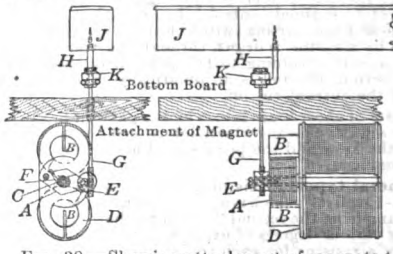


FIG. 38.—Showing attachment of magnets to key in a pianoforte.

at the point *P*. As soon as a perforation passes underneath, the reading finger drops down and closes the circuit through its magnet, and remains closed for a length of time that depends upon the length of the slot. The amount of current in the circuit, that is, the dynamic power of the magnet, depends upon the value of resistance included in the circuit and this is regulated by magnets which cause the comb wire *J* to move up and down over the resistor unit *H*. The magnets all operate on the rotating armature principle. Fig. 38 shows one of the magnets as attached to a key on the

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ianoforte. The armatures of these magnets are laminated to minimize the ıtarding effect of eddy currents.

270. Combination organ and piano players. Certain combinations ·e also made whereby the Tel-Electric transmitter operates a piano by ıeans of a piano music roll. By turning over a coupler, the piano is cut ıt, and the same transmitter operates the organ by means of an organ ıusic roll. With this type of combination, when the organ is coupled to ıe transmitter, the piano is played entirely automatically by means of ıe organ music sheet, so it is possible to play very closely organ and piano ·rangements, the piano part being played nearly in full on the piano and ıe orchestral or organ accompaniment played in full on the organ. In ıis combination, the piano is used manually, similar to any stop in the ·gan, by means of one of the keyboards.

THE TELEGRAPHONE

BY OTIS ALLEN KENYON

ngineer, Ray D. Lillibridge, Inc., Member, American Institute Electrical Engineers, Member Society Automotive Engineers

271. Theory. The telegraphone, which was invented by Valdemar oulsen, is based upon the peculiar magnetic properties of hard steel which ermit it to receive and retain magnetic impressions that are fixed in position. he principles of the invention may be explained with a simple model as own in Fig. 39. Assume an endless steel wire to be passed over two re-olving drums at a suitable speed. If an electromagnet (Fig. 40) is brought ıto close proximity to the traveling wire, the wire will be magnetized to a egree corresponding to the strength of the magnet. If the exciting circuit ırough the magnet is alternately opened and closed the steel wire will be-ome magnetized only during the periods when the circuit is closed and ecause of the coercive strength of steel the magnetism will remain fixed in ıe positions where it is received and not equalize itself; that is, the steel wire

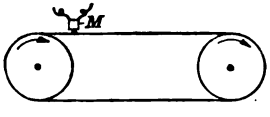


FIG. 39.—Principle of telegraphone.

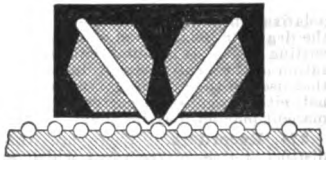


FIG. 40.—Electromagnet for wire recorder.

ıtains a permanent record of the magnetic fluctuations and if it were passed etween the poles of a suitable electromagnet it would be capable of trans-·rming the magnetic variations into electric variations by electromagnetic ıduction, the energy for which would be supplied entirely by the motor ·hich drives the wire between the poles of the magnet.

272. In the Poulsen telegraphone these principles are utilized by con-ecting a system similar to that shown in Fig. 39 to telephone instruments. ·he electric currents produced by speaking into the transmitter (Fig. 41) re used to excite the recording magnet which leaves a permanent magnetic ecord in steel that is made to travel through the magnetic field. This ecord can reproduce the sounds that generated it by passing between the ·oles of a similar magnet that is connected to a telephone receiver as shown ı Fig. 42. In order to make it possible to use the same steel over and over gain a third magnet (Fig. 43) is provided which is excited with a relatively trong and constant current in the opposite direction to the transmitting ıagnet. This magnet obliterates all previous records and leaves the steel ı condition to receive a new record.

273. Recording and obliterating. Most frequently the recording is ffected by means of a polarized electromagnet. If, for instance, the electro-

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magnet, by means of which the writing is to be performed is used to obliterate a prior magnetic record and also simultaneously magnetise the writing basis; then, during the inscription, the electromagnet is given a polarisation opposite to that which it possessed when obliterating. In this way a lively movement of the molecular magnets is obtained at the very moment of forming the writing. The susceptibility seems to increase very much in that magnetic *status nascendi*, and even shade of the writing becomes extremely perceptible. Ordinarily the polarization of the writing magnet is only a very small fraction of that of the obliterating one. The nearer its polarization approaches the neutralisation of that of the writing basis, however, the feebler may be the

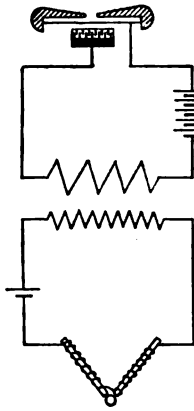


FIG. 41.—Transmitter.

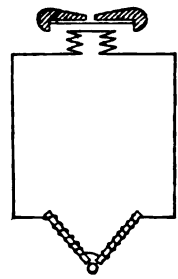


FIG. 42.—Receiver.

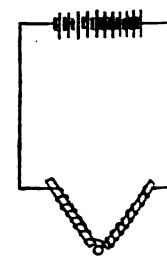


FIG. 43.—Eraser

polarisation of the obliterating magnet. The coercive force determines the degree of polarization which exactly neutralises the magnetisation of the writing basis. It is found that the writing is somewhat weak when the polarisation of the electromagnet during the process of inscription is just equal to that used in the preceding obliteration. In order to polarise the electromagnet, either a constant-current or a permanent magnet may be used.

274. Recorders. There are three distinct forms of recorders which are as follows: (a) the wire recorder; (b) the tape recorder; (c) the disc recorder.

The type of magnet used with the **wire recorder** is shown in Fig. 40, the wire being wound upon grooved drums first in one direction and then in the other. The disc and tape recorders use magnets with straight cores.

In the **tape recorder** the tape is wound up like a ribbon without any intervening substance. There is no perceptible effect from this method of procedure as experience has shown that the magnetism does not traverse the tape but is present only in the uppermost portions near the surface.

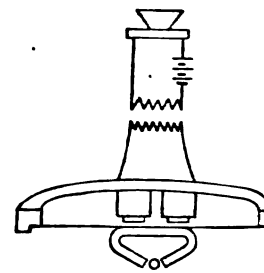


FIG. 44.—Rosenbaum's recorder

The **disc recorder** is constructed somewhat similar to the disc form of phonograph and the electromagnet is provided with a very sharp point.

275. Adaptations. There are many practical uses to which the telegraphone may be adapted and a number of commercial forms have been placed upon the market. These are described in Par. **276** to **281**.

276. Amplification of weak voice currents. In telephone work it sometimes happens that the current impulses received over the line are so

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weak that they do not furnish sufficient energy to produce records of proper magnetic intensity. However, in such cases the only effect is a diminution in the volume of sound. In an attempt to avoid this effect William A. Rosenbaum patented in 1903 a modified form of magnet for use with Poulsen's apparatus. In this improved construction a permanent magnet is used and a variation in intensity is obtained by varying the distance between the poles of the magnet and the steel record. Fig. 44 shows the principle of the construction. The permanent magnet is mounted upon an iron diaphragm which is vibrated by electric impulses received over the telephone line.

277. A type of telegraphone intended for use in connection with the ordinary telephone is so arranged that it will perform three distinct services: (a) it may be set to record all messages received during the absence of the operator; (b) it may be set to record complete telephone conversations for the purpose of accurate record; (c) it may be set to repeat messages left by the operator. When the telegraphone is set for operation during the absence of the operator it is arranged to start automatically when a call is received and to run for a definite period of time, usually 2 min. It usually begins by sending a bussing signal which apprises the speaker at the other end of the fact that the telegraphone is in operation, either to receive or transmit a message.

278. The telegraphone may be used for the repetition of telephone messages, receiving messages at one point on the steel, retransmitting them at a later point and then obliterating the record.

279. The telegraphone is also built for phonographic uses and in many ways it is superior to the best forms of wax record phonographs. Its reproduction of sound is more faithful than the phonograph, although if not shielded from external magnetic fields the records will be destroyed.

280. As a dictating machine the telegraphone has many advantages over the ordinary phonograph. For instance, it may be placed at any convenient point entirely independent of the location of the dictator and by means of a special electrical indicator the dictator is constantly informed of the operation of the machine and knows exactly the amount of unused record at his disposal. By pushing a switch he can retrace any portion of the record and have his dictation repeated to him. He also can make erasures by pushing a switch and can re-dictate in the erased portion of the record. The machines themselves are usually installed in the room with the typists, and as soon as the record is filled with dictation a bell rings and an attendant removes the record and inserts a new one. As soon as the dictation has been transcribed the record can be restored by passing it under an erasing magnet and it is then exactly as good as when new.

281. The telegraphone has also been used as a wireless receiver by installing it in connection with other regulation receiving devices.

THE TELHARMONIUM

BY OTIS ALLEN KENYON

Engineer, Ray D. Lillibridge, Inc.; Member, American Institute of Electrical Engineers; Member, Society Automotive Engineers

282. General. The telharmonium, invented by Dr. Thaddeus Cahill, produces a new form of music, by electrical means. This music offers unlimited possibilities to the composer, giving him power to produce effects which are impossible with other musical instruments. At one time there was installed in New York City a telharmonium plant of sufficient power to produce music in 10,000 places simultaneously. This plant was described by Dr. A. S. McAllister in the *Electrical World*, Vol. XLIX, 1907, p. 22. In this system the music is produced by mixing vibrations generated in a set of inductor alternators. In the New York plant there were 144 of these alternators, all geared together and driven by a constant-speed 185-h.p. motor. The frequencies of these alternators extended over a range of from 40 to 4,000 cycles per sec.

283. Circuits. The currents taken from the alternator are delivered to bus bars corresponding to the ground and partial tones. All currents composing the ground tones are superposed in one circuit, all the currents for the second partial in another and so on with other orders of harmonics. Each

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of these bus bars is closed through the primary of a closed iron-core transformer. The secondaries of these transformers are connected through impedance rheostats with a common circuit which in turn includes an impedance rheostat and is closed through the primary of an open iron-core transformer. The secondary of this transformer includes a number of impedance rheostats and is closed through the primary of an air-core transformer. The secondary of the air-core transformer contains a number of taps permitting the choice of secondary voltage for transmission to suit the impedance of the line. In this circuit is included a telephone receiver which translates the composite vibrations of the music.

284. Theory of operation. Thus it is seen that the vibrations supplied from the alternators are collected into composite ground tones and partial tones by a system of buses, and that these composite tones are regulated by the impedance rheostats, in the secondary of the iron-core transformer which are operated by stops. The rheostat in the primary circuit of the open iron-core transformer regulates the volume of the total composite vibrations, and is operated by the pedal. The impedance rheostats in the secondary of the open iron-core transformer, are used to give fine expression to the music and are manipulated constantly by the musician.

285. Connections. All the connections are made with solenoid switches, each key on the keyboard controlling a switch. The solenoids are balanced to give a minimum of inertia. All are exactly alike so that the action is uniformly prompt and precisely the same for all notes. Every detail in this entire system is the result of careful study and long experimentation. The alternators, the transformers, the switches, the rheostats and plunger magnets have all been specially worked out to fulfil the difficult conditions here required.

286. Mixed tones. In the above brief description it was assumed that we were dealing with one keyboard only, with the switches and expression devices belonging to it. One of the most striking features of this electric music is that a number of switchboards and keyboards can be connected to the same system of generators, and that these several keyboards may be made to give the same quality of tone or widely different qualities of tone, though fed from the same alternators. Thus, by mixing the harmonics of different tones in varying proportions, the musicians can give to one keyboard a wood-wind quality like that of the clarinet, to another the quality of brass, or if desired, a quality similar to that of the 'cello.

The telharmonium has beautiful qualities of tone never heard before, and resulting from the power which the performer has to mix the harmonics or overtones with the ground tones, in any desired proportions. Also, the attack and sostenuto of the instrument is surprising, in that at one instant it closely resembles wood-wind, at another brass, while at another one hears the bow on the string—according to the effect the performer wishes to produce. In its novel and singular power of controlling the timber, the attack and sostenuto, the electrical music differs from all the existing instruments of music and in a measure combines in itself the powers of the best instruments of the orchestra.

TRAIN LIGHTING SYSTEMS

BY JOHN C. BOGLE

Engineer, Cook Electric Co., Assoc. Am. Inst. Elec. Engineers

287. Systems classified. In the **head-end system**, a small turbo-generator located on the locomotive or in the baggage car serves all cars through the medium of a train line which extends from the locomotive to the rear of the train. This system is adaptable to trains which make through runs without change in make-up. Where connections and disconnections must be made or where certain cars must be cut out at points along the run the incident difficulties have rendered this method of train lighting unsatisfactory. Another system, known as the **straight-storage system**, employs a battery of 32 cells, approximating 63 volts, which may be charged at some point in the run, usually in the yards at a division point of the railroad. The advantage of this system is its simplicity, but the disadvantages due to the necessity of "spotting" cars for charge, thereby lo-

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ing time and space, together with interruptions of the yardmaster's schedule and the expense of installation and maintenance incident to a suitable charging system, have rendered this method probably the most expensive of all, everything considered. A third method of train lighting is known as the **axle-generator system.** Each car is a complete unit containing a charging generator belted to the axle of the car, a storage battery of 16 cells ("30-volt" system) feeding the lamp load, provision for maintaining proper conditions of charging, and also a device for disconnecting the generator from the battery when the rotative speed, and consequently the voltage, of the generator are inadequate for charging. See Sec. 20 and Sec. 8.

288. Charging regulators for axle-generator systems. One method which has been developed employs a charging generator which will supply constant potential independent of speed variation. Charging systems employing constant generator potential apply a voltage to the battery which approximates 2.3 volts per cell. A tapering charge is thus realised, varying from relatively high currents at low battery voltages, to lesser currents as the battery voltage increases under charge. Naturally, the degree of taper depends upon the frequency with which charging recurs and the variation of battery voltage from the start until the end of the charging period.

The other well-recognised method of regulating the charge is to maintain a constant charging current at all speeds. This is accomplished by a variation in the field strength of the charging generator. The degree of field strength is determined by the action, on a field rheostat, of a solenoid in series with one of the charging leads. Thus, the generator voltage is regulated by the current in the charging lead, and this current is thereby maintained at a satisfactory degree of constancy. Upon the termination of the charging period the generator is automatically allowed to suffer a slight diminution in voltage sufficient to float the battery and allow the generator to feed the lamps directly. Termination of the charging period may be secured by the action of a potential solenoid which operates when the voltage necessary to secure proper charging current, has reached a prescribed point. Another device, more in keeping with modern practice, provides an ampere-hour meter which terminates the charging period when a contact-making needle has travelled to a predetermined point. On discharge the meter moves in the opposite direction, and it is necessary that it be properly compensated for the error which otherwise would be introjected due to the imperfect efficiency of charge and discharge.

289. Automatic cut-out. The device employed for disconnecting the generator from the battery when the speed is below the prescribed point, is sometimes known as an automatic cut-out, which is nothing more or less than a reverse-current relay. When the generator voltage has risen to the proper value, a solenoid actuates a plunger, thereby closing a set of relay contacts and connecting the generator to the battery. Should the charging current for any cause fall below the proper value, the action of the automatic cut-out will open the contacts and disconnect the generator from the battery.

290. Polarity changer. In the operation of cars provided with axle-generator lighting systems, some provision must be made for maintaining proper generator polarity, independent of the direction of travel of the car. There are several methods of accomplishing this end, the simplest being a device whereby the brushes are shifted on the commutator through approximately 180 electrical deg. when the direction of car motion reverses. In this arrangement, the brush holders are supported in a rotatable carrier which is free to move (between well-defined limits) in response to the rotation of the armature, the motion being communicated simply by brush friction.

291. Lamp loads. In ordinary coaches the lamp loads are approximately 750 to 800 watts. This figure corresponds with modern practice to a reasonable extent, but is not conclusive, as little has been done by the railroads toward standardization of coach illumination. The Pullman Co., however, has endeavored to standardize all sleepers of an individual size, 1,600 watts for a 16-section sleeper being an example of their practice.

292. Battery capacity. Pullman sleepers carry batteries which are proportioned to the requirements of the type of run, varying from 300 to 350 amp-hr. at 30 volts. Naturally, the capacity for cars in trains making long runs with few stops may be relatively low. The 20-hr. trains

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plying between New York and Chicago have been subjected to exhaustive tests, and it has been found that in this run the batteries are required to supply the lamps for a total period of only about 1 hr. The cars of these trains carry, at present, 300 amp-hr. 30-volt batteries, but it is the consensus of opinion that, under the conditions stated, this value is considerably too high. For coaches with relatively smaller lamp load, the battery capacity ranges from 280 to 300 amp-hr., at 30 volts. Private cars meet the most severe requirements, as they are frequently compelled to stand for long intervals without charging. It is sometimes necessary to provide two sets of 350 amp-hr. batteries connected in parallel, but the use of storage batteries arranged in this manner is not considered good practice.

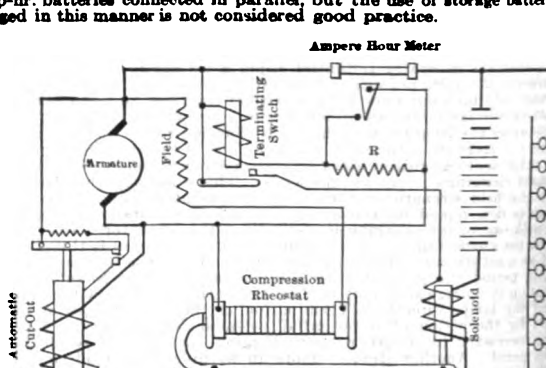


FIG. 45.—Simplified diagram of typical train-lighting system.

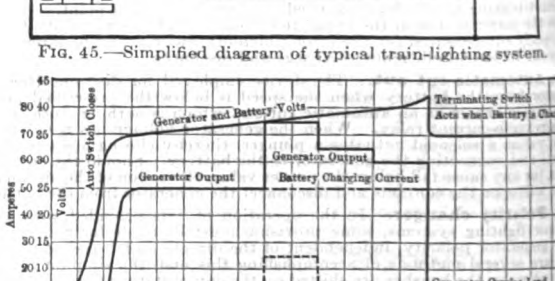


FIG. 46.—Curves illustrating performance of U-S-L-Axle equipment with type S-2 panel, starting from stand-still, with various lamp loads, and finally with battery fully charged.

293. Operation of a typical system. Fig. 45 is a diagram showing the essential elements of a typical axle-generator train-lighting system. The automatic cut-out acts primarily in response to the pull of its potential winding when the generator speed and voltage have attained their proper values. This action, as will be seen, connects the battery with a source of charging current. At the same time, the charging current is maintained constant

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by the pull due to the series winding of a solenoid, acting on a compression rheostat in series with the generator field. Meanwhile, the ampere-hour meter is running in the direction of "charge," and, when the contact-making needle has reached its point of contact, the resistance, *R*, is short-circuited. By this means, the solenoid of the terminating switch becomes sufficiently energized to close the contact points, thereby energising the potential winding of the solenoid governing the field rheostat. This pull is added to the action of the series winding, and the effect is a sudden reduction in generator voltage by such percentage as the regulator has been adjusted for. The battery is, by this process, floated on the supply circuit, the generator feeding the lamp load directly. See curves of Fig. 46. In this connection it is usual to employ what is known as a **lamp regulator**, in order that constant voltage may be applied to the lamps under all conditions of normal operation. Such a device consists of a potential solenoid controlling a series rheostat.

COMPASSES

BY ELMER A. SPERRY

President and Engineer, Sperry Gyroscope Company; Member, American Institute of Electrical Engineers

294. The Mariner's compass is a device for obtaining the direction of the local meridian at any point on the earth's surface without reference to terrestrial or astronomical objects. The mariner's compass may be divided into two types according to the source of the directive force.

295. Magnetic compass. The magnetic compass receives its directive force from the fact that the earth may be regarded as a bar magnet, one pole of which lays, at the present time, in latitude 70 deg. north and longitude 95 deg. west, the other pole being located below the south polar circle. The lines of magnetic force between these two poles pass through and encircle the earth, causing any freely suspended bar magnet on the earth's surface to line up with them.

296. Gyro compass. The gyro compass derives its directive force from the mechanical relation existing between two inter-connected gyroscopes or spinning masses. In the gyro compass system the earth rotating on its axis forms one, and the electrically driven wheel of the gyro compass forms the second.

297. Construction of the magnetic compass. The usual form of magnetic ship's compass is that devised by Sir William Thompson (Lord Kelvin) in 1878. It consists of a number of small bar magnets 2 in. or 3 in. long supported side by side in a horizontal plane, separated about ¼ in. These magnets are supported on the under side of the compass card, the card being generally 7 in. to 8 in. in diameter and extremely lightly constructed, the card being of sheet mica or aluminium. This card was usually supported on a pivot of agate or other similar very hard material; later the whole card has been furnished with an annular float, the whole element being immersed in dilute alcohol to remove a large portion of the weight from the pivot points. The compass is then mounted in horizontal gimbal rings, which are in turn supported in a stand or binnacle. Suitable illumination is provided for reading the compass at night.

298. Sources of error in magnetic compass. As the principal sources of error in the magnetic compass are due to natural phenomena which are exterior to the instrument and therefore, beyond control, it is impossible to perfectly compensate for all of them.

299. Variation. The major error is due to the fact that the lines of the earth's field are fluctuating in position and intensity due to various celestial and terrestrial disturbances, such as sun spots, earthquakes, etc. The error due to this source is known as variation, which is in reality the difference between the local magnetic field or magnetic meridian and the geographic meridian at any point on the earth's surface. This error is further exaggerated due to the fact that the position of the magnetic poles of the earth are not coincident with the geographic poles and are always moving, and the magnetic compass, therefore, must always have correction factors applied to its indications.

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300. Deviation. The second principal error in the magnetic compass known as deviation, is due to changing local magnetic conditions and the presence of magnetic material near the compass. This may be due to local magnetism of the ship itself or to material on board the ship such as gun armour plating, or magnetic cargo material. Deviation is practically absent with wooden ships, but may be present due to magnetic cargo material. It becomes increasingly troublesome with steel ships and makes the compass very unreliable and practically impossible on submarines and battleships. It is a variable quantity for varying headings of the ship and for varying inclinations from the vertical. The causes of deviation are roughly divided into:

(*a*) Quadrantal error
(*b*) Thwart ship error
(*c*) Fore and aft error
(*d*) Heeling error
(*e*) Dip

Quadrantal error in the Kelvin compass is compensated by means of two soft iron spheres which are adjusted in and out on either side of the compass. Fore and aft and thwart ship errors are compensated by means of bar magnets placed below the needle in a horisontal plane.

Heeling error and dip are compensated by means of a vertical magnet or Flinders bar placed directly beneath the pivot point of the compass card and adjustable up and down, also by a certain out of static balance condition of the system to neutralise dip.

301. Gyro compass. The principles of the gyro compass were first discovered and experimentally demonstrated by Leon Focault in 1852. However, no practical use was made of the idea until a few years ago when the first gyro compass was developed to overcome the difficulties incident to the use of the magnetic compass on war vessels where the training of the guns and shocks incident to gun fire caused such disturbances in the ship's magnetism as to make the magnetic compass inoperative.

302. Fixity of plane. The gyroscope or spinning wheel has two properties which distinguish it from ordinary non-rotating matter. "Fixity of plane" expresses the fact that whereas a wheel mounted as in Fig. 47, when not running, may be turned freely about the axis *xx* or *yy*; with this same wheel in rotation it will be found that it has a strong tendency to remain with its axis fixed in space. In other words, the gyroscope resists any force tending to change its plane of rotation.

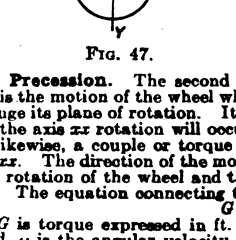


FIG. 47.

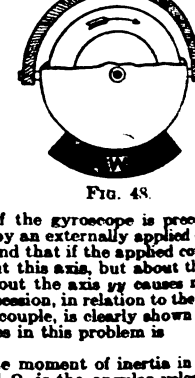


FIG. 48.

303. Precession. The second property of the gyroscope is precession which is the motion of the wheel when forced by an externally applied couple to change its plane of rotation. It will be found that if the applied couple about the axis *xx* rotation will occur not about this axis, but about the axis *yy*. Likewise, a couple or torque applied about the axis *yy* causes motion about *xx*. The direction of the motion or precession, in relation to the direction of rotation of the wheel and the applied couple, is clearly shown in the figure. The equation connecting the variables in this problem is

$$G = I\omega\Omega_p$$

where G is torque expressed in ft. lb., I is the moment of inertia in lb. ft. squared, ω is the angular velocity of spin and Ω_p is the angular velocity of precession in radians per second.

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304. Simple gyro compass. The simple gyro compass or Focault ndulum is shown in Fig. 48. It consists of a flywheel or rotor driven at a nstant speed by an electric motor and mounted in a case. This case is pported on bearings located on an axis in the horizontal plane and per-ndicular to the axis of spin of the wheel. A vertical ring supports these rizontal bearings, which ring is in turn free to rotate about the vertical is, being supported by a torsionless filament. A weight "*W*" is attached the bottom of the case which restrains the system about the horizontal arings.

305. Action of simple compass on equator. The primary require-ents of a compass are that, first, it shall be acted upon by a definite force nding to rotate it about the vertical and into the plane of the meridian, d, second, that it shall have an equilibrium position on the meridian. If consider the simple compass located on the equator and pointing east or st as shown in Fig. 49 with the axle horizontal, rotation of the earth will press forces upon and react on this system in the following manner. fter an interval of time the earth will have rotated through the angle "*A*" d the direction in space of the vertical will have changed by an amount ual to this angle. Due to the property of fixity of plane, however, the roscope will maintain its axis parallel to its original position. The result this is that the east end of the axle will have tipped up or risen in respect the earth's surface. When this has occurred the weight "*W*" will introduce gravity couple which would cause precession of the wheel about the vertical. eference to Par. 303 will show that this precession will be in such a direc-on of precession being such as to cause the wheel to rotate in the same rection as the rotation of the earth. When the wheel swings past the eridian the tilting action reverses and rotation about the vertical is soon

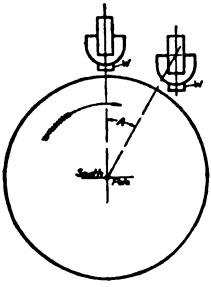


FIG. 49.

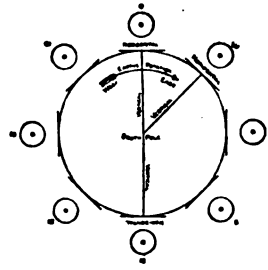


FIG. 50.

ought to a standstill and reversed and the cycle repeats. It is thus shown at such a system will seek the meridian. That its equilibrium position is the meridian is obvious from consideration of Fig. 50, which shows that tilting action is introduced when the compass is lined up with the meridian.

306. Gyro compass at any latitude. In Par. 305 above it is shown at the directive force of the gyro compass is dependent upon the component the earth's rotation about the horizontal axis in the plane of the meridian. his component is maximum at the equator and equal to the earth's rotation d it is zero at the poles. At any other latitude it is equal to $\omega \cos \lambda$ where is the angular velocity of the earth's rotation and λ is the latitude angle. he directive force of the gyro compass is, therefore, maximum at the uator and zero at the poles and proportional to the cosine of the latitude gle at any other location. The directive force of the simple gyro compass given by the equation

$$\text{Directive force} = I\omega\Omega \cos \lambda \qquad (8)$$

here the quantities are expressed in the same units as equation 7. From e above explanation will be seen that the motion of the gyro compass is an liptic oscillation performed counter-clockwise as viewed from the south.

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The motion is a simple harmonic, the period in either azimuth or tilt being given by the equation

$$T = 2\pi \sqrt{\frac{I\omega}{Mg \cdot (\Omega \cos \lambda)}}$$

307. Correction for vertical component rotation. At any other point than the equator there is a component of the earth's rotation about the vertical equal to $\Omega \sin \lambda$. For this reason an error will be introduced into the compass at latitude other than zero due to the fact that the earth will rotate beneath the tilt, tending continually to leave the axle behind the meridian. As soon, however, as the axle is displaced from the meridian a tilt or dip is introduced which brings into play the gravity couple and a new equilibrium position will be found where the tilt introduced is just sufficient to precess the compass about the vertical at the rate of $\Omega \sin \lambda$. This error may be removed and the compass axle leveled and brought into the meridian plane by hanging a weight of suitable size on the end of the axle. This introduces a new gravity couple of a correct magnetude to cause precession equal and opposite the vertical component of the earth's rotation. The size of this weight is different for each different latitude, becoming larger as the latitude angle increases. In practice the size of the weight, which, minute, is only changed for about every 10 deg. of latitude and is then effected by a slight lateral adjustment of the horizontal pivot.

308. Speed and latitude deviation. The compass when properly leveled, as described in Par. **307**, and held stationary will indicate a true geographic meridian. However, when mounted on a moving object, such as a ship, a deviation is introduced, due to this movement. It is obvious that when a ship is moving on the earth's surface in any direction, it may always be considered as revolving in a great circle, therefore the same in nature as the earth's rotation, from which the compass derives its directive force but smaller in magnitude. It therefore follows that this new apparent rotation of the earth will give the compass a tendency to line up a new plane. While this new rotation or ship's course is parallel to the equator no error is introduced since the only effect is to add or subtract from the earth's angular velocity. However, when this course lies in the meridian the deviation due to the ship's velocity is maximum while for any other heading of the ship the deviation is proportional to the cosine of the heading angle. It is further apparent that since the directive force, due to the ship's motion is constant for a given speed in any latitude, whereas, the directive force of the earth's rotation becomes smaller as the latitude angle increases, that this speed error will be of larger magnitude for a given ship's speed, the greater the latitude angle. The equation for this deviation is given by

$$S = \tan^{-1}\left(\frac{K \cos H}{900 \cos \lambda}\right)$$

where S = deviation in degrees, K = ship speed in knots and H = ship heading (meridional component).

In the gyroscopic compasses manufactured by the Sperry Gyroscope Company an ingenious device makes all these corrections, automatically solving this equation for latitudes, speeds, and headings so that all readings of the gyro compass and its repeaters are exactly on the true geographic meridian. This device automatically moves the lubber ring or reading point for the compass card a correct amount for all of the various headings, all latitudes and speeds of the ship. This form of gyro compass has been adopted as standard in practically all navies of the world.

309. Ballistic deviation. Another source of natural deviation is that known as the ballistic deviation, which is due to components of acceleration forces in the *NS* line. When a ship steaming north changes either its velocity or direction, the forces due to acceleration are impressed on the weight "*W*", which force sets up a couple about the horizontal axis of the gyroscope and in turn causes precession about the vertical. Since the speed and latitude deviation will change when the *NS* component of a ship's speed changes we may, by properly adjusting the size and lever arm of the weight "*W*," bring about a condition in which movement caused by acceleration forces is just sufficient to bring the compass to, but not beyond, its new settling point. If the weight "*W*" and its lever arm are such as to make the period as given by equation (9) equal to 85 minutes of time, there will be no oscillation as

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up by the changes of speed. This adjustment theoretically will only be correct for one given latitude, but in practice if the period is made correct for a selected latitude, the error on either side is too minute to cause trouble in navigable latitudes.

310. Methods of suspension. The directive force of the gyro compass at the equator exceeds 200,000 dyne-centimeters. This is very large compared to the magnetic compass with approximately 500 dyne-centimeters. In the gyro compass this directive force is required to orient a rather large mass and the details of the suspension are of extreme importance. There are three methods of suspension, used more or less successfully. The oldest suspension in practical use was a float. This method consisted in carrying the weight of the sensitive element on a hollow metal float immersed in oil or mercury. Sensitive ball bearings are used for centralising the system. The second has recently been developed, which consists essentially of a step bearing floated on an oil film, the film being maintained by pressure from a small pump. The pulsations of this pump apply a vertical vibratory movement to the sensitive element for the purpose of maintaining a minimum static friction. The suspension most widely adapted and completely successful is that used in the Sperry compass which consists of torsionless filament composed of a bundle of fine piano wires. This filament supports the sensitive element and is in turn supported by a second rotating "follow-up or "phantom" element. This rotating member is constantly driven by a small electric motor through a system of contacts which cause the phantom element to closely follow all motions of the sensitive element in azimuth. An important adjunct to all gyro supporting systems is means for rendering them mechanically "nascent," that is, eliminating static friction. In the Sperry compass, which was the first to embody this feature, the follow-up system is so arranged as to cause a continuance of small oscillations of the phantom element in azimuth.

311. Damping. Friction would, of course, be the most obvious means of damping the oscillations of the compass in azimuth. Friction damping works satisfactorily in the case of a stationary compass; however, when applied about either the vertical or horizontal axis of the gyroscope when mounted on a boat, it energizes this system due to the motions of the boat. The damping means employed, therefore, must be such that the damping force is proportional to the amplitude of the oscillation and must vanish when the compass comes to rest on the meridian. Damping may be applied about either the horizontal or vertical axis of the gyroscope. Any method of absorbing energy of the oscillation which would damp reservoirs of a liquid, for instance, one mounted on the north side and one on the south side of the gyro casing connected by a restricted passage which retards the flow between them, will perform this function, acting about the horizontal axis. A novel method of damping is that employed in the Sperry compass, shown in Fig. 51, where the weight "*W*" is supported on the phantom element and connected to the wheel by means of the pin (1) offset to the east of the vertical axis. It is obvious then that when the wheel tilts or dips a "couple" will be introduced, not only about the horizontal axis as in the simple compass, but also about the vertical axis. This "couple" about the vertical is in such a direction as to cause precession of the wheel about the horizontal opposite to the motion introduced by the earth's rotation. True damping in almost any desired percentage is thus secured.

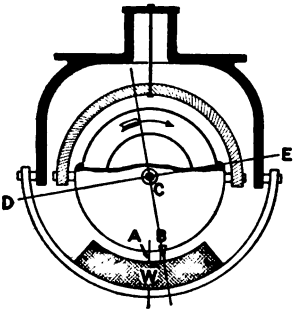


FIG. 51.

312. Mechanical details. In order to obtain the maximum directive force with the minimum of weight, it is necessary to run the wheels at as high a speed as practicable. Three-phase induction motors are preferably

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used for driving the wheels, which rotate at speeds from 8,000 to 20,000 r.p.m., depending on the design of the compass and the size of the wheel. In order to secure smooth running wheels at these speeds great care must be exercised in balancing the wheels dynamically, and the construction must be such that no relative movement of the parts occurs under the stress of

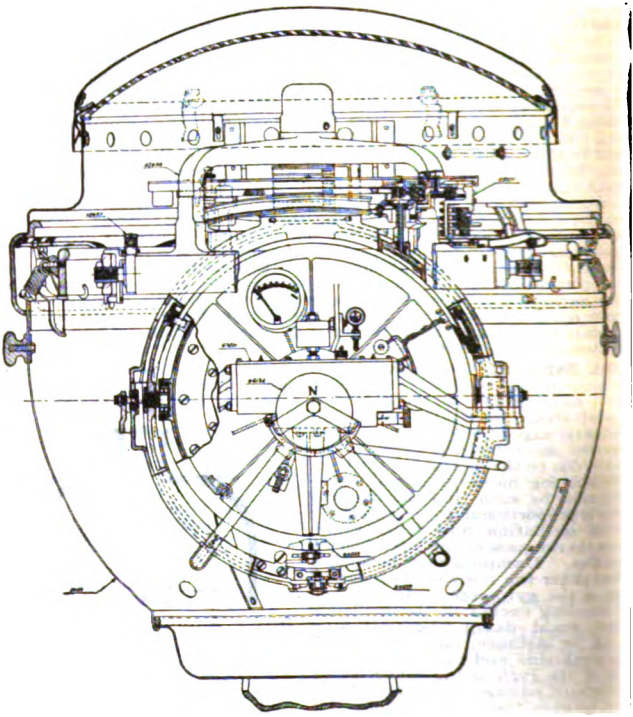


FIG. 52.

up by the rotation. Special ball-bearings must be used throughout in order to obtain the maximum of sensitivity and great care must be exercised to prevent the shifting of parts in service.

313. Compensations. Theoretically the compass for use on a ship should be so constructed that the moments of inertia about the axes of rotation (including the gimbal axes) are equal. In practice this is impossible and it is necessary to employ other compensating means to affect the result. Space does not allow a complete statement of the various means employed or of the theory upon which they are based. In general, auxiliary stabilisers and gyroscopes are used either to stabilise the entire sensitive element about the north east and east west or to stabilise the point of

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attachment between the weight and the wheel. The formof compass widely used in the Naval and Merchant Marine is shown in Fig. 52 which accomplishes the compensations by means of adjustable weights and the use of a non-pendulous mercury ballistic attachment which obtains the same meridian-seeking properties as the weight "W".

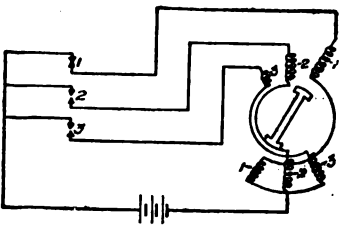


FIG. 53.

314. Repeating system. One of the outstanding advantages of the gyro compass is the fact that the directive power is so great that indications of the compass may be electrically transmitted, or repeated, to any distant point or part of the ship. This is accomplished by means of a synchronous transmitter system driven by the power-actuated phantom element. The electrical elements of the repeating system are shown in Fig. 53. One form of transmitter consists of three contacts, which are opened and closed by a cam actuated from the motions in azimuth of the phantom element. Each of these contacts energizes opposite coils of the repeater motor. In the figure position "*A*" is shown, where the contacts are closed, energizing coils 1, the armature standing as shown. In position "*B*," contacts 1 remain closed and contacts 2 are closed, the armature being rotated 30 deg., and assuming a mid-pole position. In position "*C*," contacts 1 open, and so on for a complete revolution. Suitable gearing is interposed to make each motor step equal ⅓ deg. of the compass card.

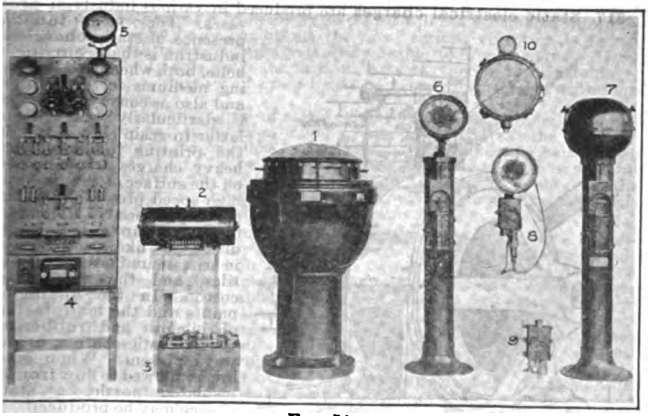


FIG. 54.

315. Typical equipment. A typical merchant marine equipment is shown in Fig. 54. It consists of the following:

1. Master gyro compass in binnacle.
2. Motor generator for converting the ship's supply into three-phase alternating current of suitable frequency for driving the gyro wheels. This machine also supplies 20-volt continuous current for operating the repeater

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system and charging the storage battery. Upon failure of the main supply this machine operates as a motor from the battery to keep the wheel spinning.

3. Storage battery for supplying current for emergency use.
4. Switchboard for controlling the various electrical circuits.
5. Alarm bells for indicating failure of the main supply.
6. Steering repeater compass and stand.
7. Bearing repeater in pelorus for taking terrestial and astronomical bearings.
8. Bulkhead repeater for us in any part of the ship.
9. Connection box to which any repeater may be connected.
10. Recording compass for recording the course of the ship and time.

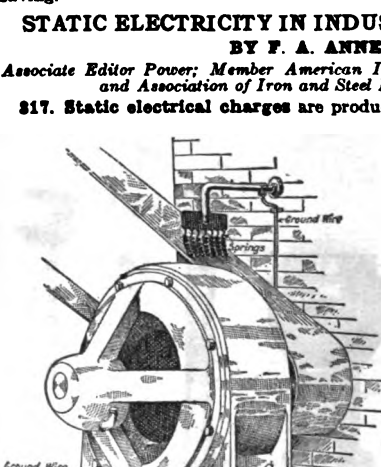
316. Operating characteristics. In practice the gyro compass not only provides a greater safety factor in navigation, but results in important economies in the operation of the ship as well. A saving of fuel is effected due to the much straighter courses steered with the gyro compass. Local disturbances, such as storms and all conditions affecting the magnetic compass are practically eliminated. In addition to this, much time is saved in the so-called "swing ship" operation for correcting the magnetic compass and in general observations and the taking of bearings are more accurate and reliable. The elimination of calculations required to derive the true geographic north from the indications of the magnetic compass, represents a reduction of liability and relieves the ships' personnel of much responsibility and allows their time to more usefully spent in operating duties. In general the increased efficiency of the ship represents a considerable percentage of saving.

STATIC ELECTRICITY IN INDUSTRIAL EQUIPMENT

BY F. A. ANNETT

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317. Static electrical charges are produced in various industrial processes. The most familiar presence of static charges in industries is that occurring in belts, both when used as driving mediums for machinery and also as conveyors. This is particularly true of the latter in grain elevators. In the printing industry very heavy charges are produced on the surface of the paper in high-speed presses; these are also experienced in the manufacture of paper. Such conditions are likewise produced in the manufacture of textiles, and the ginning of cotton. In the mixing of paints and the manufacture of oilcloth and rubberized goods, static charges are always present. When gasoline is allowed to flow from an insulated nozzle, a static charge may be produced.



DEVICE INSTALLED TO REMOVE STATIC ELECTRICITY FROM BELT

FIG. 55.

318. High-speed belts. When belts are operated at high speed in dry atmospheres, they frequently become heavily charged with static electricity. The charges are more prevalent in a cold, dry atmosphere than when it is hot and humid. When the humidity of the surrounding air is high, static charges are generally completely neutralised. Static charges

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have not been given the necessary study to determine definitely their true cause; however, they are undoubtedly the result of friction produced in various forms. In a belt there are probably three contributing causes; namely, friction of the atmosphere on the belt surface, friction between the molecule of the leather in the belt where it bends over the pulley, and slippage of the belt on the surface of the pulley. Thespeed, operating conditions, material and size of belt also have an influence. Very high potentials may be built up on belts; in one case on record, a 22-in. leather belt operating at a high rate of speed, potentials of 75,000 volts were measured. This belt was used to drive a flour mill from a motor.

319. Remedies for charged belts. When the belt runs on a wooden pulley on the driven machine and a metal pulley on the motor, or if the driven pulley is well insulated, there is the possibility that the motor will have high potentials built up on its frame, and there are cases on record where these potentials have destroyed the insulation on the windings. If the motor is equipped with ball bearings, it can generally be properly protected by effectively grounding its frame. But, when the motor is equipped with oil-ring sleeve bearings, the film of oil in the bearings may insulate the revolving element from the frame to such an extent as to allow potentials of considerable value to be built up in the former; therefore, it is necessary that the armature shaft should also be ground. This may be done through a small copper-leaf brush resting on the shaft. A common method of removing statics from belts is by suspending a metal comb near the surface and effectively grounding this comb. In some cases fine wire springs are soldered to the comb teeth and allowed to touch the surface of the belt, as in Fig. 55. The latter method, although requiring more attention to maintain on account of the springs breaking, has the advantage that the surface of the belt is directly grounded, consequently is maintained at a lower potential than when an air gap exists between it and the metal comb. The necessity of effectively grounding cannot be too strongly emphasized, since the protection, to be of value, must have an easy path to earth. Wherever possible the ground wire should be connected to a water pipe, a clamp being used to attach the wire to the pipe. The ground wire should also be installed in such a way as to protect it from injury so that it will not fail at some inopportune time. Under many conditions the most serious objection is that a belt charged with static electricity is disagreeable to work around. However, where inflammable gases and dust are present, there is always a danger of an explosion, a number of cases being on record where such explosions have been caused.

To prevent the building up of static potentials on belts, where explosive mixtures are present, it has been found advantageous to treat the belt with a dressing in which graphite has been mixed. This makes the belt surface sufficiently conductive to allow the positive and negative charges to neutralize each other. With this method it is necessary to keep a close check on the belt to be sure that the dressing has not been worn off, which may be done with a gold-leaf electroscope held near the belt.

320. In grain elevators and attrition mills, serious trouble is experienced from static charges not only in the belts driving the machinery, but also in conveyor belts and in the mills. Grain that is smutty has been found to cause high static charges in belt conveyors. In one case a rubber-belt conveyor traveling at about 750 ft. per minute, was found to have potentials of 45,000 volts. Investigations have shown that higher potentials exist in all parts of elevator equipment when handling smutty grain than when handling clean grain. Grain, when passing over metal surfaces, almost always produces electrification, in which cases the metal is positively charged and the grain passing over it is negatively charged. Explosions in grain elevators, attrition mills, threshing machines, etc., have been caused by static charges building up in various parts of the equipment and discharging to ground or from one part of the equipment to another. Effectively grounding all metal parts of the machinery has been found to be the most effective way of eliminating these hazards. It is not enough to ground the stationary parts of the equipment, but the moving parts must also be grounded, the latter through a brush rubbing on the shaft. Where machinery is driven by belts, it is possible for a potential to be built up in the machine from the belt unless the former is properly grounded. A state of

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electrification to the extent of causing an explosion may exist in metal tubing through which grain or dust passes, in blower-fans, elevator heads, scouring machines, grinding mills, etc.

321. In textile mills considerable trouble is experienced in the carding and spinning processes with static electricity developed by the pressure of the fibers between the rolls and the friction of the fibers on one another. The charges on the textiles are usually of positive polarity. As in other cases the temperature and climatic conditions have a marked influence upon these charges, they being most severe in cold, dry air and disappearing entirely in hot, humid atmosphere. Static charges are more prevalent with colored than with white stock. These charges result in a repulsion between the fibers, which causes them to have a tendency to stick out radially instead of lying parallel. These conditions are generally most severe in a dry, cold atmosphere and may become so bad as not only to interfere with production but also to have a deleterious effect upon the quality of the product. Humidifying the air with steam jets, vapor pots, wetting, etc., have been found effective, but this moisture always tends to rust the machinery and is objectionable on that account. One method that is proving very effective in many installations is a high-voltage alternating-current neutraliser, which consists of a coil giving about 12,000 volts on the secondary, one terminal of this coil being connected to a properly insulated metal rod having a number of points which are brought down to within 1 to 3 in. of the material. These charges the surrounding air alternately, positive and negative, so that when the material that is statically charged comes into the influence of this field it will be neutralised whether the charge be positive or negative.

322. In paper manufacturing and printing more or less trouble is experienced from static electricity. Wherever paper or fabric is subject to pressure or friction against solid material, static charges are most conspicuous right at the point of separation from any solid against which it has been pressed. Voltage measurements taken by the spark-gap method have shown potentials to exist varying from 5,000 to 100,000 volts, according to climatic conditions. These charges have become of such magnitude as to set the paper on fire in the press. Paper as it comes from the impression cylinder of a printing press invariably has a uniform negative charge over its surface, but before reaching the delivery it may have some spots that are negatively charged, while others may be positively charged. This is naturally what would be expected, since in the delivery the paper passes over bodies that cover only part of its surface, such as tapes, wooden fly sticks, etc. Humidifying the atmosphere is one means of overcoming the charges. It has also been found that when it is practicable, heating the surface of the paper as it comes from the press, over a gas flame, is effective in removing static. Allowing the paper to pass through the field of a high-voltage alternating current has been found to be effective in a large majority of cases.

323. In the manufacturing of paints and the grinding of pigments static charges are produced in the materials, and if the solvents are inflammable, there is always danger of fire, especially if high-speed apparatus is used. Many fires have been known to be caused by statics in these processes. Grounding of the apparatus is not always a preventative. Therefore it is good practice to have a fire extinguisher near at hand to be used on a moment's notice.

324. Handling gasoline. Explosions and fires have occurred from static discharges in handling gasoline. When gasoline or other distillates are poured at a high rate from a nozzle into a tank that is insulated from the ground, a static charge will be produced in the tank. If the nozzle is grounded and happens to be brought near the tank after the latter has become charged, there will be a discharge from the tank to the nozzle, causing a spark. If a proper mixture of air and vapor exists an explosion is very likely to result. The most effective remedy is to make sure that not only the receiving tank, but also the nozzle, is effectively grounded.

325. Miscellaneous. There are numerous other conditions in industries where static charges are produced; for example, in rubber-spreading machinery, spot-proofing machinery, naphtha-cleaning machines and the like. A wide web of cloth in a rubber-coating machine has been found to be positively charged on the central portion where the edges would be negatively charged.

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with the result that a spark may discharge across the surface of the cloth, leaving a black mark. The remedies referred to in the foregoing may be applied.

326. Grounded metal frameworks. Static electrical charges are created in industrial equipment under so many different conditions that it is impossible to suggest any hard-and-fast rule for eliminating them. What may give complete satisfaction in one case has been found to fail entirely under similar conditions in another locality. Two similar machines may be operating in close proximity to each other, and one will be practically free of static electricity, or if static charges are produced they will be easily eliminated, where with the other machine all means of preventing apparently fail. However, there is one invariable rule, whether it gives the necessary relief or not—the frame of all equipment where static charges are present should be effectively and permanently ground.

327. Reference literature. See "Static Electricity in Attrition Mill and Methods of Removal," by M. E. McCollam; "Recent Investigations of Static Conditions in Industrial Plants," by H. E. Roethe, proceedings of conference of men engaged in grain-dust explosion and fire-prevention campaign, conducted by United States Grain Corporation in cooperation with Bureau of Chemistry, U. S. Dept. of Agriculture, Apr. 22–24, 1919.

ENGINEERING SPECIFICATIONS AND CONTRACTS

328. Contracts. Since a contract which is good in law embraces for the most part questions which are wholly legal in character, it is beyond the function of an engineering handbook to go into the matter. The advice of competent legal counsel is always advisable in all matters connected with contracts, even though the engineer may have acquired an extensive knowledge of the law of contracts. Such knowledge should never be relied upon as a final guide, but is frequently useful in assisting the engineer to avoid serious mistakes and difficulties. The bibliography appended hereto is recommended as a course of reading for engineers who wish to equip themselves with a general knowledge of the subject.

329. Specifications. An engineering specification is almost always made part of a contract, either by direct embodiment in the contract or by reference. It is therefore essential that such a specification should be clear, direct, definite, conclusive, and legally sound. The art of drawing specifications is acquired necessarily by practice, founded upon a thorough technical knowledge of the subject matter in hand. General rules for guidance have been formulated by numerous authorities and references to a number of these will be found in the appended bibliography. These general rules will usually be found helpful as to the proper or desirable scope of the subject matter in a specification, but it is frequently more helpful to have before one a specification covering similar or identical subject matter which was drawn by a competent engineer. If no other source is available, the specifications used by the U. S. Government are sometimes obtainable through the Supt. of Documents, at Washington, D. C.

330. Bibliography on engineering contracts and specifications.

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SECTION 23

MECHANICAL SECTION

COMPILED FROM STANDARD AUTHORITIES

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SECTION 23

MECHANICAL SECTION

ELEMENTS OF SECTIONS

1. Definitions. The properties of structural sections commonly met in engineering practice may be reduced to certain mathematical forms which are used to simplify the calculations of design. These are defined as follows:

A. Area of section, expressed in sq. in.

R. Radius of gyration. The distance in in. from the axis of moments of the section to the point or line at which its area is considered concentrated; the radius of gyration is equal to the square root of the quotient obtained by dividing the moment of inertia of the section (taken about the same axis) by the area of the section.

I. Moment of inertia. The summation, expressed in inches to the fourth power, of the products of the elementary areas of a section by the squares of their distances from the centre of gravity or any other axis assumed for purposes of computation.

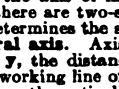
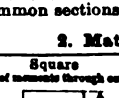
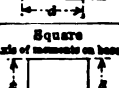
S. Section modulus. The moment of inertia divided by the distance, n, from the axis of moments to the extreme fibre. In an unsymmetrical section there are two-section moduli for each axis of moments, the least of which determines the safe unit stress.

Neutral axis. Axis of moments through centre of area.

$\bar{x}$ and $\bar{y}$, the distance or distances in an unsymmetrical section from the back or working line of the section to the centre of gravity of the section.

These mathematical expressions for the working values of a number of the more common sections, are given in Par. **2.**

2. Mathematical Properties of Sections*

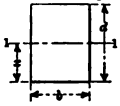
Square Axis of moments through centre 	$A = d^2$ $\bar{x} = \frac{d}{2}$ $I_{1-1} = \frac{d^4}{12}$ $S_{1-1} = \frac{d^3}{6}$ $r_{1-1} = \frac{d}{\sqrt{12}} = 0.288675d$
Square Axis of moments on base 	$A = d^2$ $\bar{x} = d$ $I_{1-1} = \frac{d^4}{3}$ $S_{1-1} = \frac{d^3}{3}$ $r_{1-1} = \frac{d}{\sqrt{3}} = 0.577350d$
Square Axis of moments on diagonal 	$A = d^2$ $\bar{x} = \frac{d}{\sqrt{2}} = 0.707107d$ $I_{1-1} = \frac{d^4}{12}$ $S_{1-1} = \frac{d^3}{6\sqrt{2}} = 0.117851d^3$ $r_{1-1} = \frac{d}{\sqrt{12}} = 0.288675d$

* "Pocket Companion," Carnegie Steel Co., 1913.

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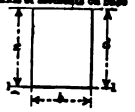
2. Mathematical Properties of Sections.—*Continued*

Rectangle
Axis of moments through center



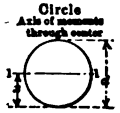
$$A = bd$$
$$x = \frac{d}{2}$$
$$I_{1-1} = \frac{bd^3}{12}$$
$$S_{1-1} = \frac{bd^2}{6}$$
$$r_{1-1} = \frac{d}{\sqrt{12}} = 0.288675d$$

Rectangle
Axis of moments on base



$$A = bd$$
$$x = d$$
$$I_{1-1} = \frac{bd^3}{3}$$
$$S_{1-1} = \frac{bd^2}{3}$$
$$r_{1-1} = \frac{d}{\sqrt{3}} = 0.577350d$$

Circle
Axis of moments through center



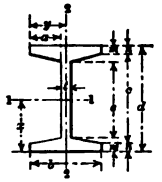
$$A = \frac{\pi d^2}{4} = 0.785398d^2$$
$$x = \frac{d}{2}$$
$$I_{1-1} = \frac{\pi d^4}{64} = 0.049087d^4$$
$$S_{1-1} = \frac{\pi d^3}{32} = 0.098175d^3$$
$$r_{1-1} = \frac{d}{4}$$

Hollow Circle
Axis of moments through center



$$A = \frac{\pi(d^2 - d_1^2)}{4} = 0.785398(d^2 - d_1^2)$$
$$x = \frac{d}{2}$$
$$I_{1-1} = \frac{\pi(d^4 - d_1^4)}{64} = 0.049087(d^4 - d_1^4)$$
$$S_{1-1} = \frac{\pi(d^4 - d_1^4)}{32d} = 0.098175\frac{(d^4 - d_1^4)}{d}$$
$$r_{1-1} = \frac{\sqrt{d^2 + d_1^2}}{4}$$

BEAM

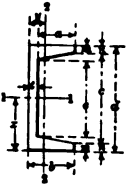


$$A = dt + 2a(m+n)$$
$$x = \frac{d}{2}$$
$$y = \frac{b}{2}$$
$$I_{1-1} = \frac{bd^3 - \frac{a}{4(m-n)}(c^4 - e^4)}{12}$$
$$I_{2-2} = \frac{2nb^3 + et^3 + \frac{m-n}{4a}(b^4 - t^4)}{12}$$

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2. Mathematical Properties of Sections.—*Continued*

CHANNEL



$$A = dt + a(m+n)$$

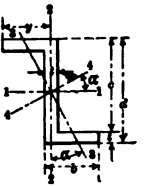
$$x = \frac{d}{2}$$

$$y = \frac{b^2 n + \frac{ct^2}{2} + \frac{a(m-n)}{3}(b+2t)}{A}$$

$$I_{1-1} = \frac{bd^3 - \frac{a}{8(m-n)}(c^4 - e^4)}{12}$$

$$I_{2-2} = \frac{2nb^3 + ct^3 + \frac{m-n}{2a}(b^4 - t^4)}{3} - Ay^2$$

ZEE



$$A = t(d+2a)$$

$$x = \frac{d}{2}$$

$$y = \frac{2b-t}{2}$$

$$\text{Tan } 2\alpha = \frac{(dt-t^2)(b^2-bt)}{I_{1-1} - I_{2-2}}$$

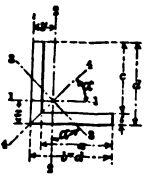
$$I_{1-1} = \frac{bd^3 - a(d-2t)^3}{12}$$

$$I_{2-2} = \frac{d(b+a)^3 - 2a^3c - 6ab^2c}{12}$$

$$I_{3-3} = \frac{I_{2-2}\cos^2\alpha - I_{1-1}\sin^2\alpha}{\cos 2\alpha}$$

$$I_{4-4} = \frac{I_{1-1}\cos^2\alpha - I_{2-2}\sin^2\alpha}{\cos 2\alpha}$$

EQUAL ANGLE



$$A = t(b+c)$$

$$x = \frac{b^2+ct}{2(b+c)}$$

$$y = x$$

$$\alpha = 45°$$

$$I_{1-1} = \frac{t(b-x)^3 + bx^3 - a(x-t)^3}{3}$$

$$I_{2-2} = I_{1-1}$$

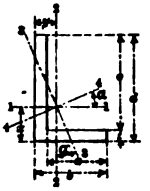
$$I_{3-3} = \frac{ct^3 + c^3t + 3ct(b-4x+2t)^2 + t^4 + 6t^2(2x-t)}{12}$$

$$I_{4-4} = \frac{ct^3 + c^3t - 3ctb^2 + t^4}{12}$$

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2. Mathematical Properties of Section.—*Continued*

UNEQUAL ANGLE



$$A = t(b+c)$$

$$x = \frac{t(b+2c)+c^2}{2(b+c)}$$

$$y = \frac{t(2a+d)+a^2}{2(a+d)}$$

$$\text{Tan } 2\alpha = \frac{t[(2y-t)d(d-2x)+a(2x-t)(b+t-2y)]}{2(I_{1-1}-I_{2-2})}$$

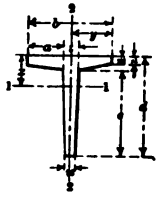
$$I_{1-1} = \frac{t(d-x)^3+bx^3-a(x-t)^3}{3}$$

$$I_{2-2} = \frac{t(b-y)^3+dy^3-c(y-t)^3}{3}$$

$$I_{3-3} = \frac{I_{2-2}\cos^2\alpha - I_{1-1}\sin^2\alpha}{\cos 2\alpha}$$

$$I_{4-4} = \frac{I_{1-1}\cos^2\alpha - I_{2-2}\sin^2\alpha}{\cos 2\alpha}$$

TEE



$$A = \frac{e(t+u)}{2} + mt + a(m+n)$$

$$x = \frac{6an^2+2a(m-n)(m+2n)+3td^2-e(t-u)(3d-e)}{6A}$$

$$y = \frac{b}{2}$$

$$I_{1-1} = \frac{e^3(3u+t)+4bm^3-2a(m-n)^3}{12} - A(x-m)^2$$

$$I_{2-2} = \frac{nb^3+(m-n)t^3+eu^3}{12} + \frac{a(m-n)[2a^2+(2a+3t)^2]}{36} + \frac{e(t-u)[(t-u)^2+2(t-2u)^2]}{144}$$

BEAMS

3. Moments. The moment of a force with respect to any given point is equal to the product of the force and its perpendicular distance from the point. If the force is expressed in lb. and the distance in in., the moment will be expressed in in-lb.

4. Reaction at supports. In the case of a horizontal beam supported at two or more places, each support reacts against the beam, and the sum of all these reactions is equal to the combined weight of the beam and its loading.

5. Shear. The loads and the reactions of the supports are vertical forces tending to shear or cut the beam across, and the stresses they produce within the beam are, therefore, called shearing stresses. The shearing force at any section is the force with which the part of the beam on one side of the section tends to slide past the part on the opposite side. The shear at each support is equal to the reaction of the support; the shear at any point between the supports is equal to the reaction of the support less the total load between the support and the point; or if the upward reaction is considered as positive and the downward loads are considered as negative, the shear at any point is the algebraic sum of all the forces acting vertically on the beam on either side of the point considered.

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6. Bending moment. The loads on the beam and the reactions of the supports constitute external forces which produce bending stresses in the beam. The summation of the moments of the external forces about the supports is called the bending moment and varies from point to point. It attains a maximum value at a point where the shear is zero.

7. Calculation of maximum bending moment. The general method for the computation of the maximum bending moment of a beam supported at the ends and loaded at various points is as follows:

First. Find the reaction at the left (or right) support by multiplying each load by its distance from the right (or left) support and dividing the sum of the products by the length of the span.

Second. Starting from the left (or right) end of the beam add the successive loads until a point is reached where the sum of the loads equals the reaction of the left (or right) support; at this point the bending moment will be a maximum. Determination of the point of zero shear and maximum bending moment may be facilitated by plotting the shear at a succession of points with respect to the distances of the points from a fixed point, such as a support. Where the shear changes sign, *viz.*, where the curve crosses the axis, may be readily noted.

Third. Multiply the reaction at the left (or right) support by its distance from the point of maximum bending moment and subtract the sum of the products of all loads to the left (or right) of this point by the corresponding distance from this point; the difference between these moments is the maximum bending moment.

In Par. 8 are given expressions for the bending moments of beams for a variety of loadings, using the following notation:

A	= Area of section, in sq. in.
n	= Distance from centre line of gravity to extreme fibre, in in.
I	= Moment of inertia about centre line of gravity, in in.^{4}
M	= Static moment, in in.^{3}
S	= Section modulus $= I/n$, in in.^{3}
r	= Radius of gyration $= \sqrt{I/A}$, in in.
f	= Bending stress in extreme fibre, in lb. per sq. in.
f_b	= Resistance of web, in lb. per sq. in.
E	= Modulus of elasticity, in lb. per sq. in.
L	= Length of section, in ft.
l	= Length of section, in in.
d	= Depth of section, in in.
b	= Width of section, in in.
t	= Thickness of section, in in.
W, W_1, W_2	= Superimposed loads supported by beam, in lb.
w	= Superimposed l ad, in lb. per unit length or area.
W *max*	= Maximum safe load at point given, in lb.
R, R_1	= Reactions at points of support, in lb.
V	= Vertical shear, in lb.
M, M_1, M_2	= Bending moments at points given, in in-lb.
M *max*	= Maximum bending moment, in in-lb.
M_r	= Maximum resisting moment, in in-lb. $= fI/n = fS$.
D, D_1	= Deflections at points given, in in.
D max	= Maximum deflection at point given, in in.

8. Bending Moment, Deflection and Shear of Beams under Various Loading Conditions*

I. CANTILEVER BEAM—Concentrated load at free end



R_1 (max. shear)	$= W$
M, distance x	$= Wx$
M max. at R_1	$= Wl$
W max.	$= \frac{fS}{l}$
D max.	$= \frac{Wl^3}{3EI}$

* "Pocket Companion," Carnegie Steel Co.

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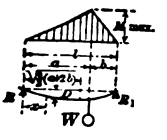
Bending Moment, Deflection and Shear of Beams under Various Loading Conditions.—*Continued*

I. CANTILEVER BEAM—Uniformly distributed load



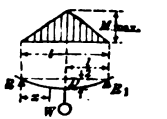
R_1 (max. shear)	$= W$
M, distance x	$= \frac{Wx^2}{2l}$
M max. at R_1	$= \frac{Wl}{2}$
W max.	$= \frac{2fS}{l}$
D max.	$= \frac{Wl^3}{8EI}$

II. BEAM SUPPORTED AT ENDS—Concentrated load near one end



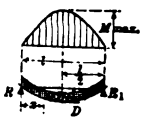
R(max. shear if $b>a$)	$= \frac{Wb}{l}$
R_1(max. shear if $a>b$)	$= \frac{Wa}{l}$
M, distance x	$= \frac{Wbx}{l}$
M max. at point of load	$= \frac{Wab}{l}$
W max.	$= \frac{fSl}{ab}$
D max.	$= \frac{Wab(a+2b)\sqrt{3a(a+2b)}}{27EIl}$

V. BEAM SUPPORTED AT ENDS—Concentrated load at centre



R (max. shear) $= R_1$	$= \frac{W}{2}$
M, distance x	$= \frac{Wx}{2}$
M max., at point of load	$= \frac{Wl}{4}$
W max.	$= \frac{4fs}{l}$
D max.	$= \frac{Wl^3}{48EI}$

BEAM SUPPORTED AT ENDS—Uniformly distributed load

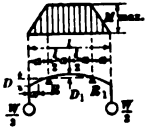


R(max. shear) $= R_1$	$= \frac{W}{2}$
M, distance x	$= \frac{Wx}{2}(1-\frac{x}{l})$
M max. at centre	$= \frac{Wl}{8}$
W max.	$= \frac{8fs}{l}$
D max.	$= \frac{5Wl^3}{384EI}$

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8. Bending Moment, Deflection and Shear of Beams Under Various Loading Conditions.—*Continued*

VI. BEAM CONTINUOUS OVER TWO SUPPORTS—Two extern symmetrical loads



R(max. shear) $= R_1 = \frac{W}{2}$

M, distance $x = \frac{Wx}{2}$

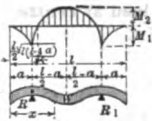
M max., from R to $R_1 = \frac{Wa}{2}$

W max. $= \frac{2fS}{a}$

D, distance $a = \frac{Wa(3al - 4a^2)}{12EI}$

D_1, distance $\frac{l}{2} - a = \frac{Wa(l-2a)^2}{16EI}$

VII. BEAM CONTINUOUS OVER TWO SUPPORTS—Uniformly distributed load



R(max. shear) $= R_1 = \frac{W}{2}$

M, distance $x = \frac{W(x^2 - lx + al)}{2l}$ 0, if $x = \frac{l}{2} \pm \sqrt{\frac{l(l+4a)}{4}}$

M_1 at R and $R_1 = \frac{Wa^2}{2l}$ max. if $a > l(\sqrt{\frac{1}{2}} - \frac{1}{2})$

M_2 at centre $= \frac{W(l-4a)}{8}$ max. if $a < l(\sqrt{\frac{1}{2}} - \frac{1}{2})$

W_1 max. $= \frac{2lfS}{a^2}$ max. if $a > l(\sqrt{\frac{1}{2}} - \frac{1}{2})$

W_2 max. $= \frac{8fS}{l-4a}$ max. if $a < l(\sqrt{\frac{1}{2}} - \frac{1}{2})$

9. Beam calculations. The fundamental beam formula, for bending is

$$M = \frac{fI}{y} \text{ or } f = \frac{My}{I} \qquad (1)$$

where M is the maximum permissible bending moment in in-lb., y the distance in in. from the neutral axis to the extreme fibre, I is the moment of inertia expressed in in. to the fourth power, and f is the allowable working stress. If M is the bending moment at the most strained section under the breaking load, f is termed the **modulus of rupture**.

* Lanza, G. "Applied Mechanics;" John Wiley & Sons, New York; Chap. VI.

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The bending moment M may be calculated from one of the formulas given n Par. 8; I may be selected from the group of sections represented in Par. . Safe working values of f depend largely upon the class of service to which he member will be put. The allowable working stress is equal to the nodulus of rupture divided by the factor of safety.

Eq. 1 may be presented in a more simplified form as

$$M = Sf \tag{2}$$

where S is the section modulus (see Par. 1).

10. Safe unit stresses for steel beams. The allowable unit stresses for eneral structural work will not usually depart from the following values* xpressed in lb. per sq. in.; care, however, should be exercised in the assump- ion of unit stresses for structures which will be called upon to meet unusual equirements.

Tension, net section, rolled steel	16,000
Direct compression, rolled steel and steel castings	16,000
Bending, on extreme fibres of rolled shapes, built sections, girders, and steel castings	16,000
Bending on extreme fibres of pins	24,000
Shear on shop rivets and pins	12,000
Shear on bolts and field rivets	10,000
Shear—average—on webs of plate girders and rolled beams, gross section	10,000
Bearing pressure on shop rivets and pins	24,000
Bearing on bolts and field rivets	20,000

11. Safe unit stresses for wooden beams. A table of allowable work- ng stresses for structural timber is given in Sec. 4. The proper factor of afety is usually determined by the character or conditions of service.

12. Concrete beams and floor slabs. The arrangement of concrete eams follows the same principles as in structural-steel construction. On hort spans, floor cross beams may be omitted, or used only at columns in rder to secure lateral stiffness. Beams are usually designed as tee beams, nd a part of the floor slab thus comprises part of the beam. The width of he slab considered to act as part of the beam should not exceed five times he slab thickness.

The reinforcement of floor slabs may be of small rods, wires or metal fabric, he latter especially on cross spans. Cross reinforcement of small rods or ires about 2 ft. apart laid parallel to the beam supporting the slab, hould be used to prevent cracks, shrinkage, etc. If the length of the slab xceeds one and one-half times its width, the entire load should be carried y transverse reinforcement. The distribution of the load on a rectangular lab supported on four sides and reinforced in both directions may be ap- roximately determined by the formula

$$R = \frac{l^4}{l^4 + b^4} \tag{5}$$

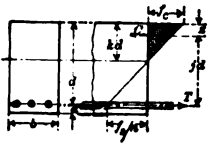
where R is the ratio of the load, l the length and b the width of the slab. n effective bond should be provided at the junction of the beam and the lab, and if the principal reinforcement of the slab is parallel to the beam, ransverse reinforcement should be used extending over the beam and well nto the slab.

In the calculation of shear or web reinforcement, concrete may be assumed o carry one-quarter to one-third of the total shear, the remainder being taken y additional reinforcement arranged at intervals equal to the depth of the eam. The usual method of reinforcing beams against failure by diagonal ension or shear, is to use bent rods or stirrups in either a vertical or inclined osition. The longitudinal spacing of such rods or stirrups should not xceed three-fourths of the depth of the beam.

* "Pocket Companion," Carnegie Steel Co., 1913; pp. 126 and 127.

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13. Formulas for rectangular concrete beams reinforced for tension only.*



$$kd = d(\sqrt{2pn + (pn)^2} - pn)$$

$$z = \tfrac{1}{3}kd$$

$$M_s = f_s A j d = f_s p j b d^2$$

$$M_c = \tfrac{1}{2} f_c k j b d^2$$

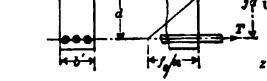
$$f_s = \frac{M}{Ajd} = \frac{M}{pjbd^2}$$

$$f_c = \frac{2M}{jkbd^2} = \frac{2pf_s}{k}$$

Steel ratio, balanced reinforcement, $p = \dfrac{1}{2\dfrac{f_c}{f_s}\left[\dfrac{f_c}{nf_c} + 1\right]}$

f_s = Tensile unit stress in steel, in lb. per sq. in.
f_c = Compressive unit stress in concrete, in lb. per sq. in.
E_s = Modulus of elasticity of steel, in lb. per sq. in.
E_c = Modulus of elasticity of concrete, in lb. per sq. in.
n = Elasticity ratio, $E_s \div E_c$.
M = Bending moment, in in-lb.
M_s = Moment of resistance of steel, in in-lb.
M_c = Moment of resistance of concrete, in in-lb.
A = Area of steel section, in sq. in.
b = Width of beam, in in.
d = Depth of beam to centre of steel reinforcement, in in.
k = Ratio of depth of neutral axis to effective depth, d.
j = Ratio of lever arm of resisting couple to depth, d.
z = Distance, top to resultant of compression, in in.
jd = Arm of resisting couple, in in. $= d - z$.
p = Ratio of steel area to area of rectangle, bd, $= A \div bd$.
kd = Distance from top of beam to neutral axis, in in.

14. Formulas for reinforced-concrete tee beams.*



$$kd = \frac{2ndA + bt^2}{2nA + 2bt}$$

Neutral axis in flange—use formulas for rectangular beams.

Neutral axis in stem—

$$z = \frac{t(3kd - 2t)}{3(2kd - t)}$$

$$M_s = f_s A j d \qquad f_c = \frac{M}{Ajd} = \frac{f_s n(1-k)}{k}$$

$$M_c = \frac{f_c b t (kd - \tfrac{1}{2}t) jd}{kd} \qquad f_c = \frac{M kd}{bt(kd - \tfrac{1}{2}t) jd}$$

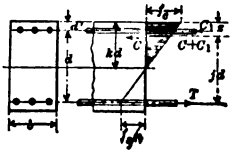
b = Width of flange, in in.
b' = Width of stem, in in.
t = Thickness of flange, in in.
p = Ratio of steel area to area of rectangle, bd, $= A \div bd$.

* Approved by Committee of Am. Soc. of Civil Eng. on Concrete and Reinforced Concrete (Proc. A.S.C.E., Vol. XXXIX—No. 2, Feb., 1913).

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15. Formulas for rectangular concrete beams reinforced for compression.*

$$kd = d\left[\sqrt{2n(p+p'\frac{d'}{d})+n^2(p+p')^2}-n(p+p')\right]$$



$$z = \frac{\frac{1}{3}k^3d+2p'nd'(k-\frac{d'}{d})}{k^2+2p'n(k-\frac{d'}{d})}$$

$$f_s = \frac{M}{pjbd^2} = \frac{nf_c(1-k)}{k}$$

$$f_s' = \frac{nf_c(k-\frac{d'}{d})}{k}$$

$$f_c = \frac{6M}{bd^2\left[3k-k^2+\frac{6p'n}{k}(k-\frac{d'}{d})(1-\frac{d'}{d})\right]}$$

A' = Area of compressive steel, in sq. in.
p' = Steel ratio for compressive steel.
f'_s = Unit compressive stress in steel, in lb. per sq. in.
C = Total compressive stress in concrete, in lb. per sq. in.
C' = Total compressive stress in steel, in lb. per sq. in.
d' = Depth to centre of compressive steel, in in.
z = Depth to resultant of $C+C'$, in in.

16. Shear and bond in reinforced concrete beams.*

Rectangular Beams	$f_v = \frac{V}{bjd}$	(6)	$f_u = \frac{V}{fd\Sigma o}$	(7)
T Beams	$f_v = \frac{V}{b'jd}$	(8)	$f_u = \frac{V}{jd\Sigma o}$	(9)

V = Total shear, in lb.; f_v = Unit shearing stress in concrete, in lb. per sq. in.; f_u = Unit bonding stress in concrete, in lb. per sq. in.: Σ_o = Sum of the perimeters of the tension bars.

17. Unit allowable stresses in reinforced-concrete beams. The following working stresses are in current use for reinforcing bars of medium structural steel and good Portland cement and gravel concrete of a 1 : 2 : 4 or 1 : 2½ : 5 mixture:

= unit compressive stress of concrete	650 lb. per sq. in.
= unit shearing stress of concrete,	
straight reinforcement	30 to 40 lb. per sq. in.
special shear reinforcement	60 to 100 lb. per sq. in.
= unit bond stress of concrete,	
smooth rods	60 to 80 lb. per sq. in.
deformed bars	100 to 175 lb. per sq. in.
= unit tensile stress of steel	16,000 lb. per sq. in.
= unit compressive stress of steel	10,000 lb. per sq. in.

$= E_s \div E_c = 15$.

For notation, see Par. 13 to 16.

COLUMNS

18. Discussion of column formulas. Due to the tendency to buckling, compression members are assumed to carry bending stresses. Failure of a column may, then, be due to direct compression, to bending or to a combination of both. No rigorous formula has ever been deduced for columns under all conditions of loading. However, several empirical formulas (Par. 21) have proven satisfactory when checked by tests made on full-sized members. All these formulas take into consideration the properties of the section (Par.), the allowable unit stress and the ratio of slenderness (Par. 20).

19. Radius of gyration is defined in Par. 1. For purposes of computation it is more convenient to employ the radius of gyration than either the moment of inertia or the section modulus.

* See footnote, Par. 13 and 14.

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20. Ratio of slenderness is the unsupported length of the compression member divided by its radius of gyration (Par. 1). The term "unsupported" refers to the length of member which is free to deflect transversely, unhampered by bracing. The maximum allowable ratio of slenderness, in usual construction, is 120 for main members under steady stress. But this ratio, however temporary the loading, should in no case exceed 200.

21. Steel-column Formulas, and Allowable Unit Stresses*

† $\frac{l}{r}$	A. B. Co. $\frac{19{,}000-100\frac{l}{r}}{13{,}000}$ max.	A. R. E. Ass'n Chicago $\frac{16{,}000-70\frac{l}{r}}{14{,}000}$ max.	Gordon $\frac{12{,}500}{1+\frac{l^2}{36{,}000r^2}}$	New York $15{,}200-58\frac{l}{r}$	Phila-delphia $\frac{16{,}250}{1+\frac{l^2}{11{,}000r^2}}$	Boston $1+\frac{l^2}{20{,}000}$
0	13,000	14,000	12,500	15,200	16,250	16,000
10	13,000	14,000	12,460	14,620	16,100	15,925
20	13,000	14,000	12,365	14,040	15,680	15,690
30	13,000	13,900	12,195	13,460	15,020	15,310
40	13,000	13,200	11,970	12,880	14,185	14,815
50	13,000	12,500	11,690	12,300	13,240	14,220
60	13,000	11,800	11,365	11,720	12,240	13,560
70	12,000	11,100	11,000	11,140	11,240	12,850
80	11,000	10,400	10,615	10,560	10,275	12,120
90	10,000	9,700	10,205	9,980	9,360	11,390
100	9,000	9,000	9,785	9,400	8,510	10,670
110	8,000	8,300	9,355	8,820	7,740	9,970
120	7,000	7,600	8,930	8,240	7,035	9,300
130	6,500	6,900	8,510	.....	6,405	
140	6,000	6,200	8,095	.....	5,840	
150	5,500	5,500	7,690			
160	5,000		7,305			
170	4,500		6,935			
180	4,000		6,580			
190	3,500		6,240			
200	3,000		5,920			

Name of formula	Abbreviation	Maximum ratio of l/r	
		Main members	Bracing struts
American Bridge Company	A. B.	120	200
American Railway Engineering Ass'n	A. R. E.	100	120
Chicago Building Law	C.	120	150
Gordon	G.	.....	.....
New York Building Law	N.Y.	120	.....
Philadelphia Building Law	P.	140	.....
Boston Building Law	B.	120	.....

22. Combination of compression and bending stresses. When a column, in addition to its axial load, carries an eccentric load, bending stresses

* "Pocket Companion," Carnegie Steel Co., 1913; p. 254.
† See Par. **20.**

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are produced. In Fig. 1 a column is pictured as carrying a beam supported on a bracket with a load W_1, and also a direct loading W. Selection of the proper column size may be accomplished by repeated trials, using the following formula:

$$f \geq \frac{w+w_1}{A} + \frac{Mn}{I} \qquad \text{(lb. per sq. in.)} \qquad (10)$$

where W and W_1 are expressed in lb.; A is the area of the column section in sq. in.; M is the bending moment in in-lb., ($=w_1 x$) due to eccentric loading; n is the distance of the extreme fibre from the neutral axis, measured in the direction of bending; and f is the allowable axial unit compression stress, in lb. per sq. in.

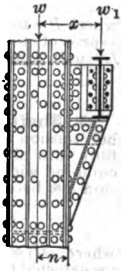


FIG. 1.—Column with eccentric superposed load.

23. Wooden columns. * The safe load tables of wooden columns which follow, based upon the working unit stresses adopted by the American Railway Engineering Association, give the allowable direct compressive loads for square and round columns.

The safe loads of rectangular columns may be found from the safe loads of square columns by direct proportion of areas, using the safe load unit stress of the square column whose side is equal to the least side of the rectangular section.

The following table gives the safe load in lb. per sq. in. of sectional area for ratios of

$$\frac{l}{d} = \frac{\text{effective length of column, in in.}}{\text{least side or diameter, in in.}} \qquad (11)$$

ranging between limits of 15 and 30.

Unit Working Stresses in Lb. per Sq. In.

$\frac{l}{d}$	Longleaf pine, white oak	Douglas fir, Western hemlock	Shortleaf pine, spruce, bald cypress	White pine, tamarack	Red cedar, redwood	Norway pine
	$1{,}300\times(1-l/d60)$	$1{,}200\times(1-l/d60)$	$1{,}100\times(1-l/d60)$	$1{,}000\times(1-l/d60)$	$900\times(1-l/d60)$	$800\times(1-l/d60)$
15	975	900	825	750	675	600
16	953	880	807	733	660	587
17	931	860	788	717	645	573
18	910	840	770	700	630	560
19	888	820	752	683	615	547
20	867	800	733	667	600	533
21	845	780	715	650	585	520
22	823	760	697	633	570	507
23	802	740	678	617	555	493
24	780	720	660	600	540	480
25	758	700	642	583	525	467
26	737	680	623	567	510	553
27	715	660	605	550	495	440
28	693	640	587	533	480	427
29	672	620	568	517	465	413
30	650	600	550	500	450	400

24. Concrete columns may be reinforced by means of longitudinal bars, by bands or hoops, or by both. The general effect of the banding or hooping is to permit the use of somewhat higher working stresses; the value

* "Pocket Companion," Carnegie Steel Co., 1913; p. 327.

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P, given in the formula which follows, refers to longitudinal steel reinforcement only:

$$P = f_c(A_c + nA_s)$$

where P = total load on column, in lb.; A_c = area of concrete in sq. in.; A_s = area of steel in sq. in.; f_s = unit compressive stress in steel in lb. per sq. in.; f_c = unit compressive strength of concrete; $n = f_s/f_c$. See Par. 17.

SHAFTING

25. Shaft design. When shafting carries pulleys, the stresses due to belt tension tend to create a bending back and forth, which throws any given fibre into alternate tension and compression. These bending stresses must combine with the shearing stresses due to twisting. The following expression has been offered by Rankine, based on the theory of elasticity.*

$$f = \frac{r}{2I}[M_1 + \sqrt{M_1^2 + M_2^2}]$$

where M_1 = greatest bending moment; M_2 = greatest twisting moment; r = external radius of shaft; I = moment of inertia of the section about a diameter; f = greatest allowable unit stress at outside of fibre. In calculating the bending moment introduced by belting, it must be remembered that the force applied is equal to the sum of the tensions in the two sides of the belt.

It may be more convenient to use a table of horse-powers transmitted at various speeds by shafts of standard sizes. See Par. 27.

26. Horse-power Transmitted by Line Shafts,† Bearings over 8 ft. $\text{H.p.} = \frac{D^3R}{75}$

Diam. of shaft, in.	Rev. per min.								
	1	50	100	150	200	250	300	400	500
1 3/16	0.0223	1.12	2.23	3.35	4.46	5.58	6.70	8.93	11.16
1 7/16	0.0396	1.98	3.96	5.94	7.92	9.90	11.88	15.84	19.80
1 11/16	0.0641	3.20	6.41	9.61	12.81	16.02	19.22	25.63	32.04
1 15/16	0.0970	4.85	9.70	14.55	19.39	24.24	29.09	38.79	48.49
2 3/16	0.1396	6.98	13.96	20.93	27.91	34.89	41.87	55.82	69.78
2 7/16	0.1931	9.65	19.31	28.96	38.62	48.28	57.93	77.24	96.55
2 11/16	0.2588	12.94	25.88	38.82	51.76	64.70	77.64	103.5	129.4
2 15/16	0.3380	16.90	33.80	50.69	67.59	84.49	101.4	135.2	169.0
3 3/16	0.4318	21.59	43.18	64.77	86.36	108.0	129.5	172.7	215.9
3 7/16	0.5416	27.08	54.16	81.23	108.3	135.4	162.5	216.6	270.8
3 11/16	0.6685	33.43	66.85	100.3	133.7	167.1	200.5	267.4	334.2
3 15/16	0.8139	40.70	81.39	122.1	162.8	203.5	244.2	325.6	407.0
4 7/16	1.165	58.25	116.5	174.8	233.0	291.3	349.5	466.0	
4 11/16	1.605	80.24	160.5	240.7	321.0	401.2	481.4	641.9	
5 1/2	2.218	110.9	221.8	332.7	443.7	554.6	665.5		
6	2.880	144.0	288.0	432.0	576.0	720.0	864.0		
6 1/2	3.662	183.1	366.2	549.2	732.3	915.4			
7	4.573	228.7	457.3	686.0	914.7	1143.0			
7 1/2	5.620	281.3	562.5	843.8	1125.0				
8	6.827	341.3	682.7	1024.0	1365.0				

* Lanza, G. "Applied Mechanics," John Wiley & Sons, New York, 1907, p. 338.

† Data Book No. 125, Link-Belt Co., 1914.

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27. Horse-power of Shafts for Simply Transmitting Power.

$$\text{H.p.} = \frac{D^3R}{50}$$

Diam. of shaft, in.	Rev. per min.								
	1	50	100	150	200	250	300	400	500
1 1/16	0.0335	1.67	3.35	5.02	6.70	8.37	10.05	13.40	16.74
1 1/8	0.0594	2.97	5.94	8.91	11.88	14.85	17.82	23.76	29.70
1 1/16	0.0961	4.81	9.61	14.42	19.22	24.03	28.83	38.44	48.05
1 1/4	0.1455	7.27	14.55	21.82	29.09	36.37	43.64	58.18	72.73
2 1/16	0.2094	10.47	20.94	31.40	41.87	52.34	62.80	83.74	104.7
2 1/8	0.2896	14.48	28.96	43.45	67.93	72.41	86.89	115.9	144.8
2 1/4	0.3882	19.41	38.82	58.23	77.64	97.05	116.5	155.3	194.1
2 1/2	0.5069	25.35	50.69	76.04	101.4	126.7	152.1	202.8	253.5
3 1/16	0.6477	32.39	64.77	97.15	129.5	161.9	194.3	259.1	323.9
3 1/8	0.8124	40.62	81.24	121.9	162.5	203.1	243.7	324.9	406.2
3 1/4	1.003	50.14	100.3	150.4	200.6	250.7	300.8	401.1	501.4
3 1/2	1.221	61.04	122.1	183.1	244.2	305.2	366.2	488.3	610.4
4 1/16	1.748	87.38	174.8	262.1	349.5	436.9	524.3	699.0	
4 1/8	2.407	120.4	240.7	361.1	481.5	601.8	722.5	962.9	
5 1/16	3.328	166.4	332.8	499.1	665.5	831.9	998.2		
6	4.320	216.0	432.0	648.0	864.0	1080.0	1296.0		
6 1/2	5.493	247.6	549.3	823.9	1099.0	1373.0			
7	6.860	343.0	686.0	1029.0	1372.0	1715.0			
7 1/2	8.438	421.9	843.8	1266.0	1688.0				
8	10.24	512.0	1024.0	1586.0	2048.0				

GEARING AND CHAIN DRIVE

28. Toothed gearing is used for positive drive between shafts, that is, here the requirements will permit no slippage. There are two styles of eth, the cycloidal and the involute. The former is used where the distance tween centres of driving and driven member can be rigidly maintained. **ycloidal gears** do not wear so rapidly as involute gears, and are used to ansmit energy at rather high speeds. **Involute gears**, on the other hand, not require so accurate a spacing of centres, although, after wearing for me time, this advantage becomes lessened, id such gearing is no longer insensible to idly adjusted bearings. Involute teeth are icker at the root than cycloidal gears, and is added strength has considerable weight the selection of gears for high-torque service. hey operate at somewhat lower allowable eeds than cycloidal gears.

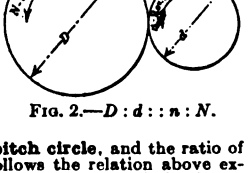


FIG. 2.—$D : d : : n : N$.

29. Gear pitch.* When, as in Fig. 2, two emental circles may be said to roll one on e other with no slippage, their speeds in rev. r min. are inversely proportional to their ameters. In the case of gearing, the ele- ental circle just mentioned is known as the **pitch circle**, and the ratio of tational speeds of a pair of meshed gears follows the relation above ex- ressed. There are two common methods of describing the pitch of gear eth. **Diametral pitch** is an expression derived by dividing the number of eth on the gear by the diameter of the pitch circle in in. Thus, an ght-pitch gear has eight teeth per in. of pitch-circle diameter. **Circular**

* Schwamb & Merrill. "Elements of Mechanism," John Wiley & Sons.

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pitch is the distance in in., measured along the pitch circle, from a point on one tooth to a corresponding point on the next tooth.

Selection of gears to accomplish a desired result, is determined by the rotational speed ratio which is sought for driver and driven member, the speed in ft. per min. at which the gear pitch circle is to rotate; and the stress to which the gears will be subjected in service.

30. Horse-power and working loads of cut steel gears.* Under the heading "w.l." is given the working load or number of pounds of pow transmitting stress which can safely be brought on each inch width tooth of a cut-steel gear or pinion of the size indicated at left of tab when it is running at the speed listed at top.

Under the heading "h.p." this is converted into horse-power transmitte at the speed named.

These figures should be multiplied by the width of working face in in. the power of the gear in question.

The ft. per min. at pitch line equals pitch diameter in in. multiplied by rev. per min. and by 0.2618.

Diametral pitch	Circular pitch	No. of teeth	Speed of pitch line (ft. per min.) 100 w.l.	100 h.p.	200 w.l.	200 h.p.	300 w.l.	300 h.p.	600 w.l.	600 h.p.	900 w.l.	900 h.p.	1200 w.l.	1200 h.p.
		12	216	0.65	190	1.13	168	1.51	127	2.30	101	2.76	84	3.01
		20	288	0.86	252	1.51	226	2.04	168	3.05	134	3.67	113	4.10
10	0.3142	40	348	1.06	305	1.82	272	2.45	204	3.72	163	4.46	134	4.96
		60	364	1.10	319	1.92	286	2.57	214	3.89	170	4.66	144	5.22
		130	384	1.17	336	2.02	298	2.69	226	4.10	178	4.85	149	5.42
		12	271	0.82	235	1.42	209	1.87	158	2.88	125	3.41	106	3.84
		20	360	1.08	312	1.87	278	2.50	209	3.80	168	4.58	139	5.10
8	0.392	40	432	1.32	379	2.28	338	3.05	252	4.59	202	5.49	168	6.10
		60	456	1.39	396	2.38	355	3.19	264	4.80	211	5.76	178	6.41
		130	480	1.46	417	2.50	372	3.36	276	5.02	221	6.02	185	6.72
		12	540	1.63	467	2.81	420	3.79	312	5.67	252	6.86	209	7.59
		20	720	2.18	624	3.74	552	5.00	420	7.65	336	9.17	278	10.11
4	0.785	40	863	2.62	755	4.54	672	6.05	505	9.18	408	11.13	336	12.20
		60	912	2.76	792	4.75	708	6.44	529	9.61	425	11.60	353	12.82
		130	960	2.90	840	5.04	745	6.70	553	10.03	444	12.10	372	13.57
		12	720	2.18	624	3.74	556	5.00	420	7.65	336	9.17	278	10.11
		20	960	2.90	840	5.04	745	6.70	558	10.13	444	12.10	372	13.57
3	1.047	40	1150	3.48	1008	6.05	895	8.06	673	12.25	540	14.72	449	16.20
		60	1205	3.64	1058	6.33	938	8.45	709	12.90	564	15.40	470	17.10
		130	1270	3.86	1110	6.65	987	8.87	745	13.55	595	16.23	494	18.00
		12	1080	3.28	935	5.62	840	7.56	625	11.35	502	13.70	418	15.20
		20	1440	4.37	1250	7.48	1120	10.10	840	15.30	672	18.32	556	20.20
2	1.57	40	1727	5.23	1512	9.07	1343	12.10	1008	18.35	835	22.80	672	24.45
		60	1820	5.52	1590	9.55	1420	12.80	1060	19.33	852	23.25	708	25.70
		130	1908	5.76	1670	10.00	1487	13.38	1110	20.20	888	24.20	741	26.90
		12	1427	4.32	1250	7.48	1110	10.00	836	15.20	667	18.20	553	20.10
		20	1920	5.80	1680	10.08	1488	13.40	1120	20.33	893	24.35	744	27.00
1½	2.09	40	2310	7.00	2015	12.10	1800	16.20	1345	24.50	1080	29.45	893	32.40
		60	2420	7.35	2112	12.68	1873	16.88	1403	25.60	1128	30.77	936	34.05
		130	2540	7.70	2220	13.33	1970	17.70	1483	26.95	1183	32.25	985	35.75

31. Gear noise at various speeds. Spur gears usually begin to make noticeable noise at pitch-line speeds above 600 ft. per min. The allowable noise is dependent upon the attendant conditions at the installation. How-

* Data Book 125, Link-Belt Co., New York, 1914, p. 107.

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ever with ordinary gears it would be exceptional to secure speeds, satisfactory from a standpoint of noise, which would range as high as 1,200 ft. per min. With herring-bone gears running in oil, pitch-line speeds as great as 5,000 ft. per min. have been reached. In the case of rawhide and cloth pinions, operation with a satisfactory minimum of noise can be attained at speeds ranging from 2,000 to 3,000 ft. per min.

32. Maximum Speed of Gearing

(A. Towler, *Engineering*, April 19, 1889, p. 388)

	(ft. per min.)	
Ordinary cast-iron wheels		1,800
Helical cast-iron wheels		2,400
Mortise cast-iron wheels		2,400
Ordinary cast-steel wheels		2,600
Helical cast-steel wheels		3,000
Special cast-iron machine-cut wheels		3,000
Double herringbone gears in oil*		5,000

33. Horse-power and working loads of cut cast-iron gears.† For significance of symbols, see Par. **30.**

Diametral pitch	Circular pitch	No. of teeth	Speed of pitch line (ft. per min.) 100 w.l.	100 h.p.	200 w.l.	200 h.p.	300 w.l.	300 h.p.	600 w.l.	600 h.p.	900 w.l.	900 h.p.	1200 w.l.	1200 h.p.
10	0.3142	12	90	0.27	79	0.47	70	0.63	53	0.96	42	1.15	35	1.27
		20	120	0.36	105	0.63	94	0.85	70	1.27	56	1.53	47	1.71
		40	145	0.44	127	0.76	113	1.02	85	1.55	68	1.86	56	2.04
		60	152	0.46	133	0.80	119	1.07	89	1.62	71	1.94	60	2.18
		130	160	0.49	140	0.84	124	1.12	94	1.71	74	2.02	62	2.26
8	0.392	12	113	0.34	98	0.59	87	0.78	66	1.20	52	1.42	44	1.60
		20	150	0.45	130	0.78	116	1.04	87	1.58	70	1.91	58	2.11
		40	180	0.55	158	0.95	141	1.27	105	1.91	84	2.29	70	2.54
		60	190	0.58	165	0.99	148	1.33	110	2.00	88	2.40	74	2.69
		130	200	0.61	174	1.04	155	1.40	115	2.09	92	2.51	77	2.80
4	0.785	12	225	0.68	195	1.17	175	1.58	130	2.36	105	2.86	87	3.16
		20	300	0.91	260	1.56	230	2.08	175	3.18	140	3.82	116	4.22
		40	360	1.09	315	1.89	280	2.52	210	3.82	170	4.64	140	5.09
		60	380	1.15	330	1.98	295	2.68	220	4.00	177	4.83	147	5.35
		130	400	1.21	350	2.10	310	2.79	230	4.18	185	5.05	155	5.64
3	1.047	12	300	0.91	260	1.56	232	2.08	175	3.18	140	3.82	116	4.22
		20	400	1.21	350	2.10	310	2.79	232	4.22	185	5.05	155	5.64
		40	480	1.45	420	2.52	373	3.36	280	5.10	225	6.14	187	6.80
		60	503	1.52	440	2.64	391	3.52	295	5.37	235	6.42	196	7.13
		130	530	1.61	462	2.77	411	3.70	310	5.64	248	6.77	206	7.50
2	1.57	12	450	1.37	390	2.34	350	3.15	260	4.73	209	5.71	174	6.33
		20	600	1.82	520	3.12	467	4.20	350	6.37	280	7.64	232	8.44
		40	720	2.18	630	3.78	560	5.04	420	7.64	348	9.50	280	10.20
		60	760	2.30	663	3.98	592	5.33	442	8.05	355	9.70	295	10.72
		130	795	2.40	695	4.17	619	5.57	462	8.40	370	10.10	309	11.23
1½	2.09	12	595	1.80	520	3.12	462	4.16	348	6.34	278	7.59	230	8.37
		20	800	2.42	700	4.20	620	5.58	466	8.47	372	10.15	310	11.28
		40	963	2.92	840	5.04	750	6.75	560	10.20	450	12.28	372	13.52
		60	1010	3.06	880	5.28	780	7.03	585	10.65	470	12.82	390	14.20
		130	1060	3.21	925	5.55	820	7.38	617	11.22	493	13.44	410	14.90

* This figure was supplied in 1913 by Mr. W. C. Bates, Engineer of the Taucus Machine Co.

† Data Book 125, Link-Belt Co., New York, 1914, p. 106.

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34. Chain drive. When the pitch-line speed does not exceed 600 ft. per min., it is possible to use **steel-roller chains** (Fig. 3) for positive transmission between two parallel shafts. These chains move on cut sprockets the rollers engaging the s... faces of the teeth being fr... to turn. For higher spee... it is customary to use a... form of **toothed** (silent) **chain** passing over toothe... wheels (Fig. 4). The mos... economical speed at which... silent chain can be operate... is from 1,000 to 1,800 ft. p... min., though by no means t... these limits impassable. Th... distance between centre... should be not less than th... sum of the diameters o... driver and driven wheel. The proper tooth combination should be deter... mined under the following considerations:

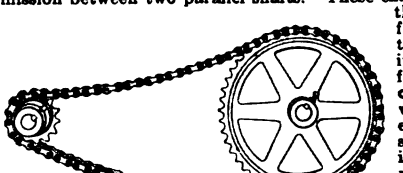


FIG. 3.—Steel-roller chain.

Pitch of chain (nominal)	⅜	½	⅝	¾	1	1¼	1½	2	2½
Minimum number of teeth in driving wheel.	15	17	17	17	17	17	17	19	19
Minimum number of teeth in driven wheel.	17	19	19	19	21	21	21	23	25
Maximum number of teeth in driver.	90	90	90	90	90	90	90	90	90
Maximum number of teeth in driven wheel.	120	130	130	130	130	130	130	130	130
Maximum rev. per min. of minimum wheel.	2260	1835	1460	1220	920	800	700	530	425
Corresponding chain speed (ft. per sec.)	1200	1300	1300	1300	1300	1400	1500	1500	1500

It is desirable to have an odd number of teeth in the pinions and an even number of links in the chain. Chains whose widths range from two times the pitch to six times the pitch, are preferable and are usually employed. Where it is possible, partiality is shown the chains of shorter pitch, as these have the advantage of greater durability and life than the narrower chains, of somewhat longer pitch, that would correspond in fulfilling the requirements.

The approximate strength (ultimate) of these chains can be obtained by multiplying the pitch in in. by the width in in., and multiplying the product by 5,500, the result being expressed in pounds.

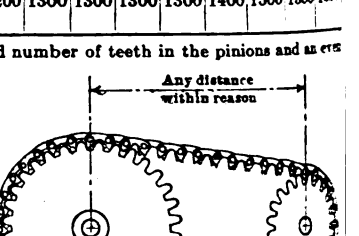


FIG. 4.—Silent-toothed chain.

BELTS AND ROPE DRIVE

35. Classification of belts. Belts are made of leather, rubber or ... cloth fabric. They are made single or double if of leather, and of several plys if their material is rubber or fabric. **Rubber belts** are adapted to installations where there is considerable moisture or high temperature. **Fabric belts** may also be used in moist places if they are sure to receive proper attention, but for all-round service these belts are not nearly so good as leather or rubber belts. **Leather belts**, if they can be kept dry, are the most satisfactory in every way.

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Diameter of pulley (in.)	Width of belt																	
	2 in.	3 in.	4 in.	5 in.		6 in.		8 in.		10 in.		12 in.	14 in.	16 in.	18 in.	20 in.	22 in.	24 in.
	S	S	S	S	D	S	D	S	D	S	D	D	D	D	D	D	D	D
	4 ply	4 ply	4 ply	4 ply	6 ply	4 ply	6 ply	4 ply	6 ply	4 ply	6 ply	6 ply	8 ply	8 ply	8 ply	8 ply	8 ply	8 ply
6	0.29	0.43	0.57	0.71	1.3													
8	0.38	0.57	0.76	0.95	1.7	1.1	2.1											
10	0.48	0.71	0.95	1.2	2.2	1.4	2.6	2.1	4.2									
12	0.57	0.86	1.1	1.4	2.6	1.7	3.1	2.5	5.0	3.1	6.3							
14	0.67	1.0	1.3	1.7	3.1	2.0	3.7	2.9	5.9	3.7	7.3	11.0						
16	0.76	1.1	1.5	1.9	3.5	2.3	4.2	3.4	6.7	4.2	8.4	12.6	14.7					
18	0.86	1.3	1.7	2.1	3.9	2.6	4.7	3.8	7.5	4.7	9.4	14.1	16.5	18.8				
20	0.95	1.4	1.9	2.4	4.4	2.9	5.2	4.2	8.4	5.2	10.5	15.7	18.3	21.0	23.6			
22	1.0	1.6	2.1	2.6	4.8	3.1	5.8	4.6	9.2	5.8	11.5	17.3	20.2	23.0	25.9	28.8		
24	1.1	1.7	2.3	2.9	5.2	3.4	6.3	5.0	10.0	6.3	12.6	18.8	22.0	25.1	28.3	31.4	34.5	
26	1.2	1.9	2.5	3.1	5.7	3.7	6.8	5.4	10.9	6.8	13.6	20.4	23.8	27.2	30.6	34.1	37.5	40.9
28	1.3	2.0	2.7	3.3	6.1	4.0	7.3	5.9	11.7	7.3	14.7	22.0	25.7	29.3	33.0	36.7	40.3	44.0
30	1.4	2.1	2.9	3.6	6.5	4.3	7.9	6.3	12.6	7.9	15.7	23.6	27.5	31.4	35.3	39.3	43.2	47.1
32	1.5	2.3	3.0	3.8	7.0	4.6	8.4	6.7	13.4	8.4	16.8	25.1	29.3	33.5	37.7	41.9	46.1	50.3
34	1.6	2.4	3.2	4.0	7.4	4.9	8.9	7.1	14.2	8.9	17.8	26.7	31.2	35.6	40.1	44.5	49.0	53.4
36	1.7	2.6	3.4	4.3	7.9	5.1	9.4	7.5	15.1	9.4	18.8	28.3	33.0	37.7	42.4	47.1	51.8	56.5
38	.....	.....	3.6	4.5	8.3	5.4	10.0	8.0	15.9	10.0	19.9	29.9	34.8	39.8	44.8	49.8	54.7	59.7
40	.....	.....	3.8	4.8	8.7	5.7	10.5	8.4	16.8	10.5	20.9	31.4	36.6	41.9	47.1	52.4	57.6	62.8
42	.....	.....	4.0	5.0	9.2	6.0	11.0	8.8	17.6	11.0	22.0	33.0	38.5	44.0	49.5	55.0	60.5	66.0
44	.....	.....	4.2	5.2	9.6	6.3	11.5	9.2	18.4	11.5	23.0	34.6	40.3	46.1	51.8	57.6	63.4	69.1
46	.....	.....	4.4	5.5	10.0	6.6	12.0	9.6	19.3	12.0	24.1	36.1	42.1	48.2	54.2	60.2	66.2	72.2
48	.....	.....	4.6	5.7	10.5	6.9	12.6	10.1	20.1	12.6	25.1	37.7	44.0	50.3	56.6	62.9	69.1	75.4
50	.....	.....	.....	6.0	10.9	7.1	13.1	10.5	20.9	13.1	26.2	39.3	45.8	52.4	58.9	65.5	72.0	78.5
60	.....	.....	.....	7.1	13.1	8.6	15.7	12.6	25.1	15.7	31.0	47.1	55.0	62.8	70.7	78.6	86.4	94.3
72	.....	.....	.....	.....	.....	10.3	18.9	15.1	30.2	18.9	37.7	56.6	66.0	75.4	84.8	94.3	103.7	113.1
84	.....	.....	.....	.....	.....	.....	.....	17.6	35.2	22.0	44.0	66.0	77.0	88.0	99.0	110.0	121.0	131.9

* Link-Belt Co., Data Book, No. 125, 1914.

S and *D* refer to thickness of leather belting; 4 ply, 6 ply, and 8 ply refer to thickness of cotton or rubber belting. 5,280 ft. per min. is the limiting speed for iron pulleys. A good belt speed is 3,500 ft. per min. If possible, use pulleys listed below zigzag line.

H ...tta Book,

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37. Belt drive. The driving force of a belt is the difference in belt tension on the tight and loose sides ($T_1 - T_2$). In ordinary practice it is usual to assume that $T_1 = 2T_2$, provided there is sufficient arc of contact on both pulleys, and that a **coefficient of friction** of about 0.22 can be realized. For leather belts on iron pulleys this coefficient may be 0.56 when dry, 0.3 when wet, 0.23 when greasy, and 0.15 when oily.*

Belts should always be run with the tight side undermost, and with the grain of the leather next the pulley surface. Where considerable power is to be transmitted, the pulley centres should be spaced about 20 or 25 ft. for best results. Shortening this distance usually necessitates additional belt tension in order to prevent an excess of slip. One form of drive which is coming into extended use is the employment of a spring or weighted idler operating on the slack side of the belt. The function of this idler, in the **short-belt drive**, is to increase the arc of contact on the pulley surface. The purpose of the whole arrangement is to economise space.

Belts which are operated at excessive tensions will occasion great annoyance and expense. Hot bearings, broken pulleys, stretched and broken belts are all attributable to this cause, and such damage not only entails the expense of its own replacement or repair but also should be held responsible for production time lost at the working machines.

38. Determination of the proper belt thickness is a much mooted question, there being excellent authority favoring directly opposite practices.†

In general it may be said that thin belts are better adapted to high speeds because of the decreased centrifugal forces secured through their use. In large belts it is usually the case that other conditions fix the choice of belt thickness.

39. Belt splicing. The best splice is the glued joint, made by beveling the ends and cementing a lapped joint. However, there are many occasions where this is not justifiable. **Belt lacing** may be done with rawhide strips or with wire. Many configurations of holes have been advanced, but, whatever lacing method is adopted, care must be taken to insure proper and permanent alignment of the ends. Enough material should be left below the holes to prevent the lacing from being torn out. Where there is considerable work of this nature to be done, it is customary to install a belt-lacing machine; this furnishes a very satisfactory and cheap method of belt splicing.

40. Length of belt.‡ Unqualifiedly the best method of determining the proper length of belt to be used over pulleys of known diameter and spacing, is by direct measurement. Sometimes, however, this cannot be done. For **open belts** the following formula may be used:

$$\text{Length} = R(\pi + 0.0349\alpha) + r(\pi - 0.0349\alpha) + 2C\cos\alpha \qquad (14)$$

where R is the radius of the larger pulley; r the radius of the smaller pulley, C the distance between centres; and α is the angle whose sine is $(R-r)/C$.

For **crossed belts**

$$\text{Length} = (R+r) \times (\pi + 0.0349\beta) + 2C\cos\beta \qquad (15)$$

where β is the angle whose sine is $(R+r)/C$.

41. Rope drive is suited to those cases where mechanical energy must be transmitted comparatively long distances, and also where the transmission is to be made at an angle or in a vertical direction. The ropes may be of hemp, steel or cotton. Manila hemp is in widest use where a multiplicity of ropes is employed, and steel cable is used chiefly for long-distance single-rope drives.

The **multiple-rope (English)** system uses a number of ropes running side by side. By the use of couplings instead of splices, unequal tensions may be compensated and repairs facilitated. In the **continuous-rope**

* Kent, William. "Mech. Eng. Pocket Book," John Wiley and Sons, New York, 1912, p. 1115.

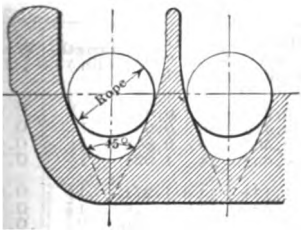
† Taylor, F. W. *Trans.* A. S. M. E., Vol. XV, p. 204.
Kent, W. *Trans.* A. S. M. E., Vol. XV, p. 242.
Barth, C. O. *Trans.* A. S. M. E., 1909.

‡ Kent, W. "Mech. Eng. Pocket Book," John Wiley & Sons, New York, 1912, p. 1125.

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erican) system, one rope is used; this is wrapped around the sheaves **esired** number of times, and then carried over from the last groove of **heave** to the first groove of the other by a guide pulley which, at the **time**, maintains a constant tension in the rope. It is clearly seen that **the** latter system is the more flexible and easily installed of the two, the **ts of a** single breakage would be much more serious.

e angle of the groove should be about as shown in Figs. 5 and 6, which **rate** the grooves used for manila, hemp, or cotton ropes on the driving **res** of both the English system and the American. For economical **the** pulleys should be not less than forty times the diameter of the rope. **ie horse-power** which can be transmitted by ropes at various speeds is **ubject** of much controversy, some engineers imposing loads greater by **40** per cent. than the recommendations of others. The data offered



5.—Standard groove of English system.

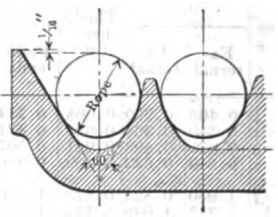


FIG. 6.—Standard groove of American system.

'ar. 42 represent conservative practice. Lanza* and the Link-Belt Co.† heir tables advocate values considerably higher, while J. J. Flather‡ is a more conservative than the accompanying authority.

42. Horse-power of Transmission Rope at Various Speeds

Speed of the rope in ft. per min.											Smallest diam. of pulley in in.
1,500	2,000	2,500	3,000	3,500	4,000	4,500	5,000	6,000	7,000	8,000	
1.45	1.9	2.3	2.7	3.0	3.2	3.4	3.4	3.1	2.2	0	20
2.3	3.2	3.6	4.2	4.6	5.0	5.3	5.3	4.9	3.4	0	25
3.3	4.3	5.2	5.8	6.7	7.2	7.7	7.7	7.1	4.9	0	30
4.5	5.9	7.0	8.2	9.1	9.8	10.8	10.7	9.3	6.9	0	36
5.8	7.7	9.2	10.7	11.9	12.8	13.6	13.7	12.5	8.8	0	42
9.2	12.1	14.3	16.8	18.6	20.0	21.2	21.4	19.5	13.8	0	54
13.1	17.4	20.7	23.1	26.8	28.8	30.6	30.8	28.2	19.8	0	60
18.0	23.7	28.2	32.8	36.4	39.2	41.5	41.8	37.4	27.6	0	72
23.1	30.8	36.8	42.8	47.6	51.2	54.4	54.8	50.0	35.2	0	84

* Lanza, G. "Notes on Friction," J. S. Cushing & Co., Boston.
† Data Book, No. 125, Link-Belt Co., New York, 1914.
‡ Flather, J. J. "Rope Driving," John Wiley & Sons, New York, 1895.
** Hunt, C. W. "Manila Rope," Cat. 054, C. W. Hunt Co., New York.

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PIPE AND SCREW THREADS

43. Pipe—Black and Galvanized

(National Tube Company Standard)

STANDARD PIPE

Size (in.)	Diameters (in.)		Thickness (in.)	Weight per ft. (lb.)		Threads per in.	Couplings		
	External	Internal		Plain ends	Threads and couplings		Diameter (in.)	Length (in.)	Weight (lb.)
⅛	0.405	0.269	0.068	0.244	0.245	27	0.562	½	0.05
¼	0.540	0.364	0.088	0.424	0.425	18	0.685	1	0.06
⅜	0.675	0.493	0.091	0.567	0.568	18	0.848	1½	0.07
½	0.840	0.622	0.109	0.850	0.852	14	1.024	1½	0.12
¾	1.050	0.824	0.113	1.130	1.134	14	1.281	1½	0.20
1	1.315	1.049	0.133	1.678	1.684	11½	1.576	1½	0.34
1¼	1.660	1.380	0.140	2.272	2.281	11½	1.950	2½	0.53
1½	1.900	1.610	0.145	2.717	2.731	11½	2.218	2½	0.74
2	2.375	2.067	0.154	3.652	3.678	11½	2.760	2½	1.10
2½	2.875	2.469	0.203	5.793	5.819	8	3.276	2½	1.72
3	3.500	3.068	0.216	7.575	7.616	8	3.948	3½	2.49
3½	4.000	3.548	0.226	9.109	9.202	8	4.591	3½	4.20
4	4.500	4.026	0.237	10.790	10.889	8	5.091	3½	4.71
4½	5.000	4.506	0.247	12.538	12.642	8	5.591	3½	5.34
5	5.563	5.047	0.258	14.617	14.810	8	6.296	4½	8.06
6	6.625	6.065	0.280	18.974	19.185	8	7.358	4½	9.55
7	7.625	7.023	0.301	23.544	23.769	8	8.358	4½	10.95
8	8.625	8.071	0.277	24.696	25.000	8	9.358	4½	13.90
8	8.625	7.981	0.322	28.554	28.809	8	9.358	4½	13.90
9	9.625	8.941	0.342	33.907	34.188	8	10.358	5½	17.25
10	10.750	10.192	0.279	31.201	32.000	8	11.721	6½	29.57
10	10.750	10.136	0.307	34.240	35.000	8	11.721	6½	29.87
10	10.750	10.020	0.365	40.483	41.132	8	11.721	6½	29.87
11	11.750	11.000	0.375	45.557	46.247	8	12.721	6½	32.55
12	12.750	12.090	0.330	43.773	45.000	8	13.958	6½	43.09
12	12.750	12.000	0.375	49.562	50.706	8	13.958	6½	43.09
13	14.000	13.250	0.375	54.568	55.824	8	15.208	6½	47.13
14	15.000	14.250	0.375	58.573	60.375	8	16.446	6½	50.43
15	16.000	15.250	0.375	62.579	64.500	8	17.446	6½	63.95

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EXTRA STRONG PIPE

Size (in.)	Diameter (in.) External	Diameter (in.) Internal	Thickness (in.)	Weight per ft. (lb.) Plain ends
¼	0.405	0.215	0.095	0.314
⅜	0.540	0.302	0.119	0.535
½	0.675	0.423	0.126	0.738
¾	0.840	0.546	0.147	1.087
¾	1.050	0.742	0.154	1.473
1	1.315	0.957	0.179	2.171
1¼	1.660	1.278	0.191	2.996
1½	1.900	1.500	0.200	3.631
2	2.375	1.939	0.218	5.022
2½	2.875	2.323	0.276	7.661
3	3.500	2.900	0.300	10.252
3½	4.000	3.364	0.318	12.505
4	4.500	3.826	0.337	14.983
4½	5.000	4.290	0.355	17.611
5	5.563	4.813	0.375	20.778
6	6.625	5.761	0.432	28.573
7	7.625	6.625	0.500	38.048
8	8.625	7.625	0.500	43.388
9	9.625	8.625	0.500	48.728
10	10.750	9.750	0.500	54.735
11	11.750	10.750	0.500	60.075
12	12.750	11.750	0.500	65.415
13	14.000	13.000	0.500	72.091
14	15.000	14.000	0.500	77.431
15	16.000	15.000	0.500	82.771

DOUBLE EXTRA STRONG PIPE

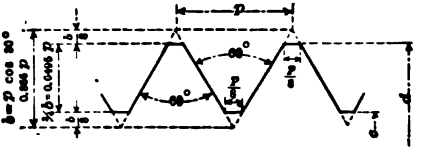
Size (in.)	Diameters (in.) External	Diameters (in.) Internal	Thickness (in.)	Weight per ft. (lb.) Plain ends
½	0.840	0.252	0.294	1.714
¾	1.050	0.434	0.308	2.440
1	1.315	0.599	0.358	3.659
1¼	1.660	0.896	0.382	5.214
1½	1.900	1.100	0.400	6.408
2	2.375	1.503	0.436	9.029
2½	2.875	1.771	0.552	13.695
3	3.500	2.300	0.600	18.583
3½	4.000	2.728	0.636	22.850
4	4.500	3.152	0.674	27.541
4½	5.000	3.580	0.710	32.530
5	5.563	4.063	0.750	38.552
6	6.625	4.897	0.864	53.160
7	7.625	5.875	0.875	63.079
8	8.625	6.875	0.875	72.424

Taper of pipe threads is ¾ in. diameter per ft. length. Report Com. Pipe and Threads, A. S. M. E., Nov., 1886.

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44. Screw Threads

(United States Standard)



Diameter		Area		No. of threads per in.	Diameter		Area		No. of threads per in.
Total d (in.)	Net c (in.)	Total dia., d (sq. in.)	Net dia., c (sq. in.)		Total d (in.)	Net c (in.)	Total dia., d (sq. in.)	Net dia., c (sq. in.)	
¼	0.185	0.049	0.027	20	2¼	2.175	4.909	3.716	4
⅜	0.294	0.110	0.068	16	2½	2.300	5.412	4.156	4
½	0.400	0.196	0.126	13	2¾	2.425	5.940	4.619	4
⅝	0.507	0.307	0.202	11	3	2.550	6.492	5.108	4
¾	0.620	0.442	0.302	10					
⅞	0.731	0.601	0.419	9	3¼	2.629	7.069	5.428	3½
					3½	2.879	8.296	6.509	3½
1	0.838	0.785	0.551	8	3¾	3.100	9.621	7.549	3½
1¼	0.939	0.994	0.693	7	3¾	3.317	11.045	8.641	3
1¼	1.064	1.227	0.890	7					
1⅜	1.158	1.485	1.054	6	4	3.567	12.566	9.993	3
1½	1.283	1.767	1.294	6	4¼	3.798	14.186	11.330	2½
1⅝	1.389	2.074	1.515	5½	4½	4.028	15.904	12.741	2½
1¾	1.490	2.405	1.744	5	4¾	4.255	17.721	14.221	2½
1⅞	1.615	2.761	2.049	5					
					5	4.480	19.635	15.766	2½
2	1.711	3.142	2.300	4½	5¼	4.730	21.648	17.574	2½
2¼	1.836	3.547	2.649	4½	5½	4.953	23.758	19.268	2½
2½	1.961	3.976	3.021	4½	5¾	5.203	25.967	21.262	2½
2¾	2.086	4.430	3.419	4½	6	5.423	28.274	23.095	2½

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SECTION 24

STANDARDS OF THE AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS

1921 REVISION

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NOTE

The Standards of the American Institute of Electrical Engineers, 1921 Revision, are reprinted with the permission of the Institute for the general information of patrons of the Handbook, but are not guaranteed to be the latest or correct edition of the Rules themselves. In all cases where it is desired to consult or quote the Rules for authoritative purposes, an official copy should be procured from the Institute. Apply to the Secretary, American Institute of Electrical Engineers, 33 West 39th Street, New York City.

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PREFACE TO 1921 EDITION

PURPOSE OF THE STANDARDS OF THE AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS

In framing these standards the chief purpose has been to define the terms and conditions which characterize the rating and behavior of electrical apparatus, with special reference to the conditions of acceptance tests.

It has not been the purpose of the standards to standardize the dimensions or details of construction of any apparatus, lest the progress of design should be hampered.

NOTE

The Standards Committee takes this occasion to draw the attention of the membership to the value of suggestions based upon experience gained in the application of the Standards to general practice.

Any suggestions looking toward improvement in the Standards should be communicated to the Secretary of the Institute for the guidance of the Standards Committee in the preparation of future editions.

SCOPE OF THE 1921 REVISION

This edition of the Standards has been completely revised in form. This was considered necessary in view both of certain intrinsic defects in the original form, and the increase in complexity due to this form not being adapted to receive the additions which are made from year to year. Furthermore several changes in substance have been made and a few sections added.

OTHER APPROVED STANDARDS

The following resolution, adopted by the Standards Committee, was approved by the Board of Directors on April 14, 1916:

"The Standards Committee, with the approval of the Board of Directors, recommends the use of the following rules and standards as adopted by other societies. These have been formally presented to the Standards Committee by the societies concerned and are found not to be incompatible with the Standards of the American Institute of Electrical Engineers."

Standardization of service requirements for motors, as printed in the 1915 report of the National Electric Light Association.

Standardization of sizes, voltages and taps for transformers, as printed in the 1916 report of the Electrical Apparatus Committee of the National Electric Light Association.

Standard specifications for magnetic tests of iron and steel, of the American Society for Testing Materials.

Report of the Joint Rubber Insulation Committee, published in the April, 1917, Proceedings of the American Institute of Electrical Engineers.

Accuracy Specifications in Sections IV and V of the **Joint Meter Code** of the Association of Edison Illuminating Companies and of the National Electric Light Association.

Accuracy Specifications in Section II of Circular 56 of the Bureau of Standards entitled **Standards for Electric Service.**

Report of the **Boiler Code Committee** of the American Society of Mechanical Engineers.

Suggested safety rules for installing and using electrical equipment in bituminous coal mines, issued as Technical Paper 138 by the Bureau of Mines.

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SECTION 24

STANDARDS

OF THE

AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS

CHAPTER I

GENERAL PRINCIPLES UPON WHICH THE A. I. E. E. STANDARDS ARE BASED

(All temperatures in this and the following chapters are given in centigrade degrees)

HEATING

1000. General principles. The general principles by reference to which the ratings of electrical machines are fixed, so far as their heating is concerned, admit that the life of insulating materials depends upon the temperatures to which these materials are subjected. Taking, as a basis, the results of experience with machinery in practical service and the results of laboratory tests of various insulating materials, limiting "hottest-spot" temperatures have been established for various classes of insulation *for purposes of standardization*. Limiting "observable" temperatures are deduced from these limiting "hottest-spot" temperatures by subtracting therefrom a specified number of degrees which, *for purposes of standardization*, represents the margin fixed between the limiting hottest spot and the limiting observable temperatures.

This margin may be designated as the "*conventional allowance.*"

1001. Methods of temperature measurement. There are three fundamental methods of temperature measurement, namely:

1. The Thermometer Method.
2. The Resistance Method, and,
3. The Embedded-detector Method.

The general principles stated in Par. **1000** permit of the use of whichever method is best suited to the class of machine, or part thereof, to be tested, by introducing appropriate values for the limiting observable temperature by each method. All the values of the observable temperatures are based upon the "hottest-spot" limitation adopted *for purposes of standardization* for the class of insulation employed.

1002. Methods of temperature measurement defined. These three fundamental methods of making temperature measurements are designated Methods 1, 2 and 3, and are defined as follows:

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Table 100. Methods of temperature measurement

Method	Description of method
1.	**Thermometer method** This method consists in the measurement of the temperature by mercury or alcohol thermometers, by resistance thermometers, or by thermocouples, any of these instruments being applied to the hottest accessible part of the completed machine. This method does not include the use of thermocouples or resistance coils embedded in the machine as described under Method No. 3.
2.	**Resistance method** This method consists in the measurement of the temperature of windings by their increase in resistance. In the application of this method, *thermometer measurements shall also be made whenever practicable without disassembling the machine,** in order to increase the probability of obtaining the highest observable temperature. The measurement indicating the higher temperature shall be taken as the "observable" temperature.
3.	**Embedded temperature-detector method** This method consists in the measurement of the temperature by thermocouple or resistance temperature detectors, located as nearly as possible at the estimated hottest spot. When Method No. 3 is used, it shall, when required, be checked by Method No. 2. The highest observable temperature obtained from the readings of the embedded detectors shall not exceed the values permitted by the Rules for Method 3, and the highest observable temperature obtained by Method 2 shall not exceed the values permitted by the Rules for Method 2

* NOTE.—As one of the few instances in which the thermometer check cannot be applied in Method 2, the rotor of a turbo alternator may be cited.

1003. Conventional allowances for the three methods of temperature measurement. The specified differences by which the "observable" temperatures shall, *for purposes of standardization*, be assumed to be lower than the "hottest spot" temperatures (which may be designated the "Conventional Allowances") are as follows:

Method 1 ..... 15 deg. cent.
Method 2 ..... 10 deg. cent.
Method 3 ..... (See following table)

Table 101. Conventional allowance for Method 3

Method 3	
For windings with two coil-sides per slot with detectors between top and bottom coil-sides (and between coil-sides and core).	5 deg. cent.
For windings with one coil-side per slot for 5,000 volts or less, with detectors between coil-side and core and between coil-side and wedge.	10 deg. cent.
For windings with one coil-side per slot form ore than 5,000 volts, with detectors between coil-side and core and between coil-side and wedge.	10 deg. cent. plus 1 deg. cent. for every kilovolt of terminal pressure of the machine above 5 kv

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1004. Classification of insulating materials. The insulations employed in electrical machinery are subdivided into three main classes, designated A, B and C and defined as follows:

Table 102. Classification of insulating materials

Class	Description of material
A.	Cotton, silk, paper and similar materials when so treated or impregnated as to increase the thermal limit, or when permanently immersed in oil; also enamelled wire. When these materials are not treated, impregnated, or immersed in oil, they are not included in Class A.
B.	Mica, asbestos and other materials capable of resisting high temperatures, in which any Class A material or binder is used for structural purposes only, and may be destroyed without impairing the insulation or mechanical qualities of the insulation. (The word "impair" is used in the sense of causing any change which could disqualify the insulation for continuous service.)
C.	Materials capable of resisting higher temperatures than Class B, such as pure mica, porcelain, quartz, etc.

*1005. **Limiting "hottest-spot" temperatures.** The limiting "hottest-spot" temperatures are, *for purposes of standardization*, taken at the following values:

For Class A material..... 105 deg. cent. (see Note 1)
For Class B material..... 125 deg. cent. (see Note 2)
For Class C material..... no limit yet specified.

If different insulating materials are used on various parts of one winding (for instance in the slot and for the end windings) the temperature of each material shall not exceed the limit set for that material.

When insulation consists of layers of materials having different temperature-limits (for instance high-temperature limit material adjacent to the copper and lower-temperature limit material adjacent to the iron or to the air) the temperature of each material shall not exceed the limit set for that material.

1006. Limiting observable temperatures. The limiting observable temperatures for use with Methods 1, 2 and 3 are arrived at by subtracting the "conventional allowances" from the limiting "hottest-spot" temperatures for insulating materials. They are set forth in table 103.

1007. Limiting observable temperature of oil. The oil in which apparatus is permanently immersed shall, in no part, have a temperature, observable by thermometer, in excess of 90 deg. cent.

1008. Standard ambient temperatures of reference. The following values are adopted for the standard ambient temperatures of reference:

For air..... 40 deg. cent.
For water..... 25 deg. cent.

These values for the standard ambient temperatures of reference apply to all conditions where the actual ambient temperature does not exceed them.

The limiting observable temperature rise must not be increased even when the ambient temperature is lower than the standard ambient temperature of reference.

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* NOTE 1.—For cotton, silk, paper and similar materials when neither treated, impregnated nor immersed in oil, the limits of observable temperature and temperature rise shall be 15 deg. cent. below the limits fixed for these materials when impregnated.

* NOTE 2.—The Institute recognizes the ability of manufacturers to employ Class B insulation successfully at maximum temperatures of 150 deg. cent. or even higher. However, as sufficient data covering experience over a period of years at such temperatures are at present unavailable, the Institute adopts 125 deg. cent. as a conservative limit for this class of insulation, and any increase above this figure should be the subject of special guarantee by the manufacturer.

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Table 103. Limiting observable temperatures

		Class A material	Class B* material
Method 1		90 deg. cent.	110 deg. cent.
Method 2		95 deg. cent.	115 deg. cent.
Method 3	For windings with two coil-sides per slot with detectors between top and bottom coil-sides and between coil-sides and core.	100 deg. cent.	120 deg. cent.
	For windings with one coil-side per slot with detectors between coil-side and core and between coil-side and wedge.	95 deg. cent. (minus 1 degree for every 1,000 volts of terminal pressure of the machine above 5,000 volts).	115 deg. cent. (minus 1 degree for every 1,000 volts of terminal pressure of the machine above 5,000 volts).

* See also Note 2, Par. **1005**.

1009. Limiting observable temperature rises. The limiting observable temperature rises in the following Table **104** are obtained by subtracting the standard ambient temperatures of reference given in Par. **1005** from the limiting observable temperatures given in Table **103**. The limiting observable temperature rises to be used in practice are given later in the Rules. They are in some cases greater and in other cases smaller than those given in Table **104**. See Par. **1010**.

Table 104. Limiting observable temperature rises

		Air cooled	
		Class A	Class B*
Method 1		50 deg. cent.	70 deg. cent.
Method 2		55 deg. cent.	75 deg. cent.
Method 3	For windings with two coil-sides per slot, with detectors between top and bottom coil-sides and between coil-sides and core.	60 deg. cent.	80 deg. cent.
	For windings with one coil-side per slot with detectors between coil-side and core and between coil-side and wedge.	55 deg. cent. (minus 1 degree for every 1,000 volts of terminal pressure of the machine above 5,000 volts).	75 deg. cent. (minus 1 degree for every 1,000 volts of terminal pressure of the machine above 5,000 volts).

* See also Note 2, Par. **1005**.

1010. General comments on special and specific cases. In the foregoing it has been assumed, for the purpose of presenting a comprehensive, logical and consistent plan, that the rules actually used in the industry are exactly in accord with the general principles. Practical experience indicates the necessity of establishing definite rules to cover special as well as specific

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cases. These cases are set forth in later chapters. Any case not specifically dealt with may come under the general principles.

1011. Comments on the method of measurement to be employed. In the absence of definite rules, the manufacturer may, on the occasion of the acceptance test, use any of the three methods for the temperature measurements. In most cases, however, restrictions on the choice of method are imposed. These are set forth in the rules.

1012. Comments on temperature limits in special cases. Temperature limits are prescribed in the rules for special cases where conditions determined by practice, by experience, or by agreements, require departures (often arbitrary) from the limits of temperature rise corresponding to the general principles.

1013. Hottest-spot temperature the primary point of reference. The hottest-spot temperature is the primary point of reference, of the "benchmark" used as the basis for the foregoing scheme or temperature delimitation. It is not employed in commercial transactions or in the ordinary course of testing or operation of electrical machinery.

1014. Observable temperature rise the working standard. The observable temperature rise is the working standard. A summary of working data with explanatory notes, will be found in Table **200.**

1015. Duration of temperature test and correction to time of shut down. Whatever method of temperature measurement be employed, it is required that:

(*a*) Operation shall be continued until constant temperatures are determined if the machine has a continuous rating, or for the full period if the machine has a short time rating, and

(*b*) When measurements cannot be made while the machine is loaded, appropriate corrections to raise the temperature readings to the time of shut down shall be applied. See Chap. II.

MECHANICAL AND COMMUTATION LIMITATIONS

These limitations are set forth in subsequent Chapters dealing with specific kinds of machines.

WAVE SHAPE

1200. The sine wave shall be considered as standard except where the departure therefrom is inherent in the operation of the system of which the machine forms a part.

DIELECTRIC STRENGTH AND INSULATION RESISTANCE*

1300. The injury produced by dielectric stress applied to insulation is related to the time during which the stress is applied. A stress up to a certain limit may be applied for an indefinite period without injury to the insulation. A somewhat greater stress will cause heating of the insulation and a progressive deterioration, eventually resulting in breakdown. Higher values of stress cause more rapid deterioration and a quicker breakdown. It is customary to determine whether machinery will withstand the voltage stresses met in practice by a preliminary test for a definite period of time at a voltage considerably higher than the normal voltage to which the machinery is to be subjected, but not high enough to produce injury to the insulation during the period of test.

1301. The test voltage which shall be applied to determine the suitability of insulation for commercial operation is dependent upon the kind and size of the machine, and its operating voltage, upon the nature of the service in which it is to be used, and upon the severity of the mechanical and electrical stresses to which it may be subjected. The voltages and other conditions of test which are recommended have been determined as reasonable and proper for the great majority of cases, and are proposed for general adoption, except when specific reasons make a modification desirable.

1400. The insulation resistance of machinery is of doubtful significance as compared with the dielectric strength. It is subject to wide variation with temperature, humidity and cleanliness of the parts. When the insulation resistance falls below prescribed values it can, in most cases of good

* See Pars. **2350** to **2380** inclusive.

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design and where no defect exists, be brought up to the required standard by cleaning and drying the machine. The insulation resistance therefore may afford a useful indication as to whether the machine is in suitable condition for application of the dielectric test.

EFFICIENCY*

1500. The conditions under which efficiency is determined are those normal to the operation of the machine. These include voltage, current, power factor, frequency, wave shape, speed, temperature, or such of these as may apply in each particular case.

1501. The efficiency at all loads of all apparatus shall be corrected to a reference temperature of 75 deg. cent.

1502. In the case of machinery, two efficiencies are recognized, conventional efficiency (Par. **3524**) and directly measured efficiency. Unless otherwise specified, the conventional efficiency is to be employed. When the efficiency of a machine is stated without specific reference to the load conditions rated load is always to be understood, whether the efficiency be the conventional or directly measured efficiency.

RATING†

1600. Principle of machine rating. (*a*) *Rating by temperature rise:* The principle upon which machine rating is based, so far as relates to thermal characteristics, has been stated in earlier sections.

(*b*) *Rating by limitations other than temperature rise:* In some machines the rating is limited by other than thermal considerations. In such cases the principle upon which machine rating is based is that the rated load, applied continuously or for a stated period, shall not cause the various limitations specified in later chapters; *e.g.*, Pars. **4250** to **4252** inclusive, to be exceeded. The rating shall be based upon the capacity as limited by heating unless the capacity as limited by other characteristics, is less.

CHAPTER II

GENERAL RULES

The expressions "machinery" and "machines" are here employed in a general sense, in order to obviate the constant repetition of the words "machinery or induction apparatus."

To ensure satisfactory results, electrical machinery should be specified to conform to the Institute Standards, in order that it shall comply in operation, with approved limitations in the following respects, so far as they are applicable.

Operating temperature
Mechanical strength
Commutation
Dielectric strength
Insulation resistance
Efficiency
Power factor
Wave shape
Regulation

OPERATION

Temperature Limits

2104. Permissible temperatures with insulations of more than one class. (*a*) If different insulating materials are used on various parts of one winding (for instance, in the slot and for the end windings) the temperature of each material shall not exceed the limit set for that material.

(*b*) When insulation consists of layers of materials having different temperature limits (for instance high-temperature-limit material adjacent to the copper and lower-temperature-limit material adjacent to the iron or to the air) the temperature of each material shall not exceed the limit set for that material.

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* See Pars. **2231** to **2233** inclusive.
† See Pars. **2202** to **2232** inclusive.

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2116. Temperatures of metallic parts of machines. (a) *Parts adjacent to insulating material:* Metallic parts of machines in contact with or ljacent to any kind of insulation, shall not attain a temperature in excess that allowed for the adjacent insulation.

(b) *Parts not adjacent to insulating material:* All parts of machines other an those covered by Par. 2116 (a) may be operated at such temperatures shall not be injurious in any other respect.

2120. Protection against short-circuit. The Institute recognizes the lf-destructibility, both mechanical and thermal, of certain sizes and types machines, when subjected to severe short-circuits, and recommends that nple protection be provided in such cases, external to the machine if ecessary.

RATING

General

2202. Expression of rating. Except where otherwise specified the achines shall be rated in terms of their avialable *output*. For exceptions e Pars. 4223, 5203, 6204 and 6223.

2204. Institute rating. The Institute rating of a machine shall be its ting when operating with a cooling medium of the ambient temperature reference specified in Pars. 2211 and 2212 and with barometric conditions ithin the range given in Par. 2215. See Pars. 2300, 2310, 2311, 4110 and 300.

Ambient Temperature of Reference and Altitude Correction

2211. Ambient temperature of reference for air. The standard ambient temperature of reference, when the cooling medium is air, shall be 0 deg. cent.

2212. Ambient temperature of reference for water-cooled machinery. For water-cooled machinery, the standard temperature of reference or incoming cooling water shall be 25 deg. cent., measured at the intake of he machine.

2213. Machines cooled by other means. Machines cooled by means ther than air or water shall receive special consideration.

2214. Outdoor machinery exposed to sun's rays. Outdoor machinery not protected from the sun's rays at times of heavy load shall receive pecial consideration.

2215. Altitude. Increased altitude has the effect of increasing the temperature rise of some types of machinery. In the absence of information n regard to the height above sea level at which a machine is intended to vork in ordinary service, this height is assumed not to exceed 1,000 meters 3,300 ft.). For machinery operating at an altitude of 1,000 meters or less, test at any altitude less than 1,000 meters is satisfactory, and no correction hall be applied to the observed temperatures. Machines intended for peration at higher altitudes shall be regarded as special. It is recommended hat when a machine is intended for service at altitudes above 1,000 meters 3,300 ft.) the permissible temperature rise at sea level shall be reduced by per cent. for each 100 meters (330 ft.) by which the altitude exceeds 1,000 neters.

Kinds of Rating

There are various kinds of rating such as:

2220. Continuous rating. A machine rated for continuous service hall be able to operate continuously at its rated output, without exceeding ny of the limitations established herein.

In the absence of any specification as to the kind of rating, the continuous ating shall be understood.

2221. Short-time rating. A machine rated for discontinuous or short-ime service (*i.e.*, service including runs alternating with stops of sufficient duration to ensure substantial cooling), shall be capable of operating at ts rated output during a limited period, to be specified in each case, without exceeding any of the limitations established herein. Such a rating is a short-time rating.

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2222. Duty-cycle operation. Many machines are operated on a cycle of duty which repeats itself with more or less regularity. For purposes of rating, either a continuous or a short-time equivalent load may be selected which shall simulate as nearly as possible the thermal conditions of the actual duty-cycle.

2223. Standard short-time ratings. The following periods shall be used for short-time ratings: 5, 10, 15, 30, 60 and 120 minutes.

*NOTE.—When, for example, a short-time rating of 10 minutes duration is adopted, and the thermally equivalent load is 25 kw. for that period, then such a machine shall be stated to have a 10-minute rating of 25 kw.

In every case the equivalent short-time test shall commence only when the windings and other parts of the machine are within 5 deg. cent. of the ambient temperature at the time of starting the test.

2224. A. I. E. E. and I. E. C. ratings. When the prescribed conditions of test are those of the A. I. E. E. Standards the rating of the machine is the Institute Rating. (See Par. **2401.**) When the prescribed conditions of the test are those of the I. E. C. Rules, the rating of the machine is the I. E. C. rating. A machine so rated in either case may bear a distinctive sign upon its rating plate. I. E. C. stands for **"International Electrotechnical Commission."**

2225. Continuous rating implied. Machines marked "A. I. E. E. Rating" or "I. E. C. Rating" shall be understood to have a continuous rating, unless otherwise marked in accordance with Pars. **2223, 2201** or **202.**

Rating by Temperature Rise

2230. Limiting observable temperature rises. The following limiting observable temperature rises have been adopted.

NOTE 1.—(*a*) The temperature of the windings of transformers and induction regulators is always to be ascertained by Method 2.

(*b*) In measuring the temperature of air blast transformers, the air supply shall be shut off immediately at the end of the temperature run and air intake shall be closed to prevent further admission of cooling air. In checking the temperatures ascertained by resistance, the readings of thermometers well distributed and in good contact with the coils shall be noted and the maximum temperature indicated by them, if higher than that determined by resistance, shall be taken as the maximum observable temperature of the windings. With the above procedure, the observable temperature rise for air-blast transformers may attain a value not in excess of 60 deg. cent. as determined by thermometer, although it must not exceed 55 deg. cent. as determined by resistance.

(*c*) Method 3 shall be applied to all stators of machines with cores having a width 50 cm. and over; it shall also be applied to all machines of 5,000 volts and over if of over 500 kv.-a. regardless of core width.

(*d*) Method 2 shall not be used for circuits of low resistance (other than transformer windings), such as interpole windings, where external joints and connections form a considerable part of the total resistance.

(*e*) For all other cases it is optional to employ either Method 1 or Method 2. (This is equivalent to authorizing Method 1 with a 5 deg. cent. lower limit of observable temperature than is permitted for Method 2.)

NOTE 2.—For cotton, silk, paper and similar materials when neither treated, impregnated nor immersed in oil, the limits of observable temperature rise shall be 15 deg. below the limits in the above table fixed for these materials when impregnated.

NOTE 3.—For enclosed machines (rotating) the limiting observable temperature rise shall be taken as 5 deg. higher than the values set forth in the Table for Items 1 and 6.

NOTE 4.—A further limitation to this Table relates to the restriction of its application to machinery for operation in locations whose altitude is not more than 1,000 meters above sea level. Recommendations relating to the limiting temperature rise for machines for operation at higher altitudes are given in Pars. **2215** and **2231.**

NOTE 5.—If different insulating materials are used on various parts of one winding (for instance in the slot and for the end windings) the temperature of each material shall not exceed the limit set for that material.

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When insulation consists of layers of materials having different tempera- limits (for instance high-temperature limit material adjacent to the per and lower temperature limit material adjacent to the iron or the air) temperature of each material shall not exceed the limit set for that terial.

ble 200. Limiting observable temperature rises for machines for operation in locations where the ambient temperature will not exceed 40 deg. cent. for air or 25 deg. cent. for water

For Class A insulation use the values in the Table.
For Class B insulation use 20 deg. cent. higher values (or 45 deg. cent. her in the cases covered by the Note in Par. 1005).
For Class C insulation no limits yet specified.

Items	Method 1	Method 2	Method 3	
			For windings with two coil-sides per slot with detectors between top and bottom coil-sides and between coil-sides and core	For windings with one coil-side per slot with detectors against core and against wedge
1. Insulated windings other than 2.3. Note 1.	50 deg. cent. Note 1	55 deg. cent. Note 1	60 deg. cent. Note 1	55 deg. cent. minus 1 deg. for every 1,000 volts by which the terminal pressure of the machine exceeds 5,000 volts). Note 1.
2. Single layer field windings with exposed surfaces uninsulated.	60 deg. cent.	60 deg. cent.		
3. Short-circuited insulated windings.	60 deg. cent.			
4. Field windings (other than 5).		55 deg. cent.		
5. Single layer field windings with exposed surfaces uninsulated.	60 deg. cent.	60 deg. cent.		
6. Windings in slots.	50 deg. cent.	55 deg. cent.		
7. Short-circuited insulated windings.	60 deg. cent.			
8. Transformers and induction regulators.		55 deg. cent.		

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2231. Exceptions to Table 200. (*a*) For cotton, silk, paper and similar materials when neither treated, impregnated nor immersed in oil, the limits of observable temperature rise shall be 15 deg. cent. below the limits given for these materials when impregnated.

(*b*) When the thermometers are applied directly to the surfaces of the windings, such as an edgewise strip conductor, or a cast copper winding, the limiting observable temperature rise shall be 10 deg. cent. higher than given for Method 1 in the table.

(*c*) For commutators, collector rings, or bare metallic surfaces not forming part of a winding, the limiting observable temperature rise shall be 15 deg. cent. higher than given for Method 1 in the table.

(*d*) Any machinery destined for use with higher ambient temperatures of cooling mediums, and also any machinery for operation at altitudes in which no provision is made in Par. **2215**, should be the subject of special guarantee by the manufacturer. The methods of test and performance set forth in these rules will, however, afford guidance in such cases.

2232. Limiting observable temperature of oil. The oil in which apparatus is permanently immersed shall, in no part, have a temperature observable by thermometer, in excess of 90 deg. cent.

TESTS

Ambient Temperature

***2300. Measurement of the ambient temperature during tests of machinery.** (*a*) *General:* The ambient temperature is to be measured by means of several thermometers placed at different points around and half way up the machine at a distance of 1 to 2 meters (3 to 6 ft.), and protected from drafts and abnormal heat radiation, preferably as in Par. **2301**.

(*b*) *Mean temperature:* The value to be adopted for the ambient temperature during a test is the mean of the readings of the thermometers (placed as above), taken at equal intervals of time during the last quarter of the duration of the test.

(*c*) *Use of idle unit:* It is sometimes desirable to avoid errors due to time lag in temperature changes, by employing an idle unit of the same size and subjected to the same conditions of cooling as the unit under test, for obtaining the ambient temperature.

2301. Oil cup. In order to avoid errors due to the time lag between the temperature of large machines and the variations in the ambient air, all reasonable precautions must be taken to reduce these variations and the errors arising therefrom. Thus, the thermometer for determining the ambient temperature shall be immersed in a suitable liquid, such as oil, in a suitably heavy metal cup. This can be made to respond to various rates of change by proportioning the amount of oil to the metal in the containing cup. A convenient form for such an oil cup consists of a massive metal cylinder, with a hole drilled partly through it. This hole is filled with oil and the thermometer is placed therein with its bulb well immersed. The larger the machine under test, the larger should be the metal cylinder employed as an oil cup in the determination of the ambient temperature. The smallest size of oil cup employed in any case shall consist of a metal cylinder 25 mm. in diameter and 50 mm. high (1 in. in diameter and 2 in. high).

Machine Temperatures

2310. Temperature rise for any ambient temperature. A machine may be tested at any convenient ambient temperature, preferably not below 10 deg. cent., but whatever be the value of this ambient temperature, the permissible rises of temperature must not exceed those given in Table **200**.

2311. Correction for the deviation of the ambient temperature of the cooling medium, at the time of the heat test, from the standard ambient temperature of reference. Numerous experiments have shown that deviation of the temperature of the cooling medium from that of the standard of reference, at the time of the heat run, has a negligible effect upon the temperature rise of machines; therefore, no correction shall be applied for this deviation.

* The cooling fluid may either be led to the machine through ducts, or through pipes, or merely surround the machine freely. In the former case the ambient temperature is to be measured at the intake of the machine itself.

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2312. Duration of temperature test of machine for continuous vice. The temperature test shall be continued until sufficient evidence vailable to show that the maximum temperature and temperature rise ıld not exceed the requirements of the rules, should the test be prolonged il the attainment of a steady final temperature.

2313. Duration of temperature test of machine with a short-time ing. The duration of the temperature test of a machine with a short-e rating shall be the time required by the rating. In every case the iivalent short-time test shall commence only when the windings and er parts of the machine are within 5 deg. cent. of the ambient tempera-e at the time of starting the test. (See Par. 2335.)

2314. Duration of temperature test for machine having more than o rating. The duration of the temperature test for a machine with re than one rating shall be the time required by that rating which pro-ces the greatest temperature rise. In cases where this cannot be deter-ned beforehand, the machine shall be tested separately under each rating.

2315. Temperature measurements during heat run. When possible ıperature measurements shall be taken during operation, as well as when machine is stopped. The highest figures thus obtained shall be adopted. order to abridge the long heating period, in the case of large machines, sonable overloads of current during the preliminary period are suggested them.

2316. Rules for correcting to time of shut-down. (*a*) Whenever a ficient time has elapsed between the instant of shut-down and the time the final temperature measurement to permit the temperature to fall, table corrections shall be applied, so as to obtain as nearly as practicable temperature at the instant of shut-down. This can sometimes be proximately effected by plotting a curve with temperature readings as linates and time as abscissas, and extrapolating back to the instant of ıt-down. In other instances, acceptable correction factors can be applied; , in the case of machines manufactured in large quantities, the correction ained from tests made on representative machines may be used.

(*b*) Exception. In cases where successive measurements show *increasing* nperatures after shut-down, the highest value shall be taken.

Details of Testing Methods

2320. Covering of thermometer. Thermometers used for taking tem-atures of machinery shall be covered by felt pads 4 cm. × 5 cm. (1½ in. × n.), 3 mm. (⅛ in.) thick cemented on; oil putty may be used for stationary l small apparatus.

2321. Temperature coefficient of copper. The temperature coefficient copper shall be deducted from the formula $1/(234.5 + t)$. Thus, at an tial temperature $t = 40$ deg. cent., the temperature coefficient of increase resistance per degree centigrade rise is $1/(274.5 = 0.00364)$. The follow-; table, deduced from the formula, is given for convenience of reference.

Table 201. Temperature coefficients of copper resistance

Temperature of the winding, in degrees centigrade, at which the initial resistance is measured	Increase in resistance of copper per degree centigrade, per ohm of initial resistance
0	0.00427
5	0.00418
10	0.00409
15	0.00401
20	0.00393
25	0.00385
30	0.00378
35	0.00371
40	0.00364

* Temperature by resistance: The temperature by resistance may be lculated by the following formula:

Let r_t = resistance at t deg. cent.

r_T = resistance at T deg. cent.

ıen $$T = \frac{r_T}{r_t}(234.5 + t) - 234.5$$

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2323. Temperature measurement of low-resistance circuit. In circuits of low resistance, where joints and connections form a considerable part of the total resistance, the measurement of temperature by the resistance method shall not be used. (Except transformers, for which see Par. 2330.)

*2323. **Location of embedded temperature detectors.** Embedded temperature detectors should be placed in at least two sets of locations. One of these should be between a coil-side and the core and one between the top and bottom coil-sides where two coil-sides per slot are used. Where only one coil-side per slot is used, one set of detectors shall be placed between coil-side and core, and one set between coil-side and wedge. A liberal number of detectors shall be employed, and all reasonable efforts, consistent with safety, shall be made to locate them at the various places where the highest temperatures are likely to occur. (See Par. 1003.)

Efficiency

†2331. **Efficiencies recognised.** Two efficiencies are recognised, conventional efficiency and directly measured efficiency. Unless otherwise specified, the conventional efficiency is to be employed. (See Pars. 2332 and 2324.)

Input and output determinations of efficiency may be made directly measuring the output by brake, or equivalent, where applicable. Within the limits of practical application, the circulating power method, sometimes described as the Hopkinson or "loading-back" method, may be used.

2332. **Normal conditions for efficiency tests.—(*a*) *General:* The efficiency shall correspond to, or be corrected to, the normal conditions herein set forth, which shall be regarded as standard. These conditions include voltage, current, power-factor, frequency, wave shape, speed, temperature, or such of them as may apply in each particular case.

(*b*) *Load:* When the efficiency of a machine is stated without specific reference to the load conditions, rated load is always to be understood, whether the efficiency be the conventional or directly measured efficiency.

(*c*) *Wave shape:* The sine wave shall be standard, unless a different wave form is inherent in the operation of the system. (See Par. 2340.)

**(*d*) *Temperature of reference:* The efficiency of all apparatus at all loads shall be corrected to a reference temperature of 75 deg. cent., but tests may be made at any convenient ambient temperature, preferably not less than 15 deg. cent.

(*e*) *Power factor:* The efficiency of alternators and transformers shall be stated at the rated power factor.

2333. Direct measurement of efficiency. (*a*) *General:* Electric power shall be measured at the terminals of the apparatus.

(*b*) *Polyphase machines:* In polyphase machines, sufficient measurements shall be made on all phases to avoid errors of unbalance.

(*c*) *Mechanical power:* Mechanical power delivered by machines shall be measured at the pulley, gearing or coupling, on the rotor shaft, thus excluding the loss of power in the belt or gear friction. (See, however, an exception in Par. 5202.)

Wave Shape

2340. Standard wave shape. The sine wave shall be considered as standard, except where departure therefrom is inherent in the operation of the system of which the electrical machine forms a part.

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* A coil-side is one of the two active sides of the coil lying in a slot.

† The need for assigning conventional values to certain losses arises from the fact that some of the losses in electrical machinery are practically indeterminable, and must, in many cases, either be approximated by an approved method of test, or else values recommended by the Institute and designated "conventional" values shall be employed for them in arriving at the "conventional efficiency."

** In calculating plant or system efficiency it may be desirable to calculate the losses in each individual machine or part of the system at the actual temperature of that transformer or part during the specified interval. These losses may be appreciably different from the losses at 75 deg. cent., which latter shall be the standard temperature of reference for all efficiency guarantees.

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Tests of Dielectric Strength

2350. Condition of machine to be tested. Commercial tests shall, general, be made with the completely assembled machine and not with ividual parts. The machine shall be in good condition, and high-voltage sts, unless otherwise specified, shall be applied before the machine is put to commercial service, and shall not be applied when the insulation resist- oe is low due to dirt or moisture. High voltage tests to determine whether ecifications are fulfilled are admissible on new machines only.

2351. Where high-voltage tests are to be made. Unless otherwise reed upon, high-voltage tests of machines shall be made at the factory.

2352. Temperature at which high-voltage tests are to be made. igh-voltage tests shall be made at the temperature assumed under normal peration or at the temperature attained under the conditions of commercial sting.

2353. Points of application of voltage. (*a*) *General:* The test voltage iall be successively applied between each electric circuit and all other ectric circuits and metal parts grounded.

(*b*) *Interconnected polyphase windings:* Interconnected polyphase wind- gs shall be considered as one circuit. All windings except that under test all be connected to ground.

2354. Frequency and wave shape of test voltage. The frequency of e testing voltage shall be not less than the rated frequency of the machine sted. A sine wave shape is recommended (See Pars. **2340** and **4351**.) The st shall be made with alternating voltage having a crest value equal to $\sqrt{2}$ times the specified test voltage.

2355. Duration of application of test voltage. (*a*) *General:* The sting voltage for machines shall be applied continuously for a period of) sec. (See exception Par. **2355** (*b*).)

(*b*) *Standard machines and devices produced in large quantities:* Standard achines and devices produced in large quantities, for which the standard st pressure is 2,500 volts or less, may be tested for 1 sec. with a test pres- ire 20 per cent. higher than the 1 min. test pressure.

2356. Standard test voltage. (*a*) *General:* The standard test voltage r all machines, except as otherwise specified, shall be twice the normal oltage of the circuit to which the machine is connected plus 1,000 volts. See exceptions Pars. **2357, 4361, 6361**.)

2357. Assembled apparatus. Where a number of pieces of apparatus re assembled together and tested as an electrical unit they shall be tested ith 15 per cent. lower voltage than the lowest required on any of the indi- idual pieces of apparatus.

2358. Measurement of voltage in dielectric strength tests. There re two methods of measuring the voltage used in making dielectric strength ests, namely:

1. The voltmeter method.
2. The spark-gap method, using either the sphere spark-gap or the needle park-gap.

***2359. Use of voltmeters and spark-gaps in dielectric tests.** When aking high voltage tests on electrical machinery every precaution must be aken against the occurrence of spark-gap discharges in the circuits from hich the machine is being tested. A non-inductive resistance of about ohm per volt of test pressure shall be inserted in series with one termi- al of the spark gap. If the test is made with one electrode grounded, his resistance shall be inserted directly in series with the non-grounded lectrode; if neither terminal is grounded one-half shall be inserted directly n series with each electrode. In either case this resistance shall be as near be measuring gap as possible and not in series with the tested apparatus. A water tube is the most suitable form of resistor.

2360. Use of spark-gap with machines of low capacitance. When he machine under test does not require sufficient charging current to dis-

* The resistance will damp high frequency oscillations at the time of reak-down and limit the resulting current.
Carbon resistors should not be used because their resistance may become very low at high voltages.

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tort the high-voltage wave shape, or change the ratio of transformation, the spark-gap should be set for the required test voltage and the testing apparatus adjusted to give a voltage at which this spark-gap just breaks down. This adjustment should be made with the machine under test disconnected. The machine should then be connected, and with the spark-gap about 20 per cent. longer, the testing apparatus again adjusted to give a voltage of the former breakdown, which is the assumed voltage of test. This voltage shall be maintained for the required interval.

2361. Use of spark-gap with machines of high capacitance. Where the charging current of the machine under test may appreciably distort the voltage wave or change the effective ratio of the testing transformer, the first adjustment of voltage with the gap set for the test voltage shall be made with the machine under test connected to the circuit and in parallel with the spark-gap.

2362. Measurements with voltmeter. In measuring the voltage with a voltmeter, the instrument should preferably derive its voltage from the high-pressure circuit, either directly or by means of a voltmeter coil placed in the testing transformer, or through an auxiliary *ratio transformer*. It is permissible to measure the voltage at other places such as the transformer primary, provided corrections can be made for the variations in ratio caused by the charging current of the machine under test, or provided there is no material variation in this ratio. In any case when the capacitance of the machine to be tested is such as to cause wave distortion, the testing voltage must be checked by a spark-gap as set forth in Pars. **2364** and **2365** or by a crest-voltage meter. If the crest-voltage meter is calibrated in crest volts its readings must be reduced to the corresponding r.m.s. sinusoidal value by dividing by $\sqrt{2}$.

2363. Measurements with spark-gaps. (*a*) *General:* If proper precautions are taken, spark-gaps may be used to advantage in checking the calibration of voltmeters for high voltage tests of machines.

(*b*) *Range of voltages:* For the calibrating purposes set forth above, the sphere gap shall be used for voltages above 50 kv., and is preferred down to 30 kv. The needle spark gap may, however, be used for voltages from 10 to 50 kv.

2364. Needle spark-gap. The needle spark gap shall be between new sewing needles, supported axially at the ends of linear conductors, which are at least twice the length of the gap. There must be a clear space around the gap for a radius at least twice the gap length.

2365. Needle-gap sparking distances. The sparking distances in air between No. 00 double long sewing needle points for various root-mean-square sinusoidal voltages shall be assumed to be as shown in Table 202.

Table 202. Needle-gap spark-over voltages

(At 25 deg. cent. and 760 mm. barometer)

R.m.s., kilovolts	Millimeters	R.m.s., kilovolts	Millimeters
10	11.9	35	51
15	18.4	40	62
20	25.4	45	75
25	33	50	90
30	41	.....	.....

* When making arc-over tests of large insulators, leads, etc., partial arc-over of the tested apparatus may produce oscillations which will cause the measuring gap to discharge prematurely. The measured voltage will then appear too high. In such tests the "equivalent ratio" of the testing transformer should be measured by gap to within 20 per cent. of the arc-over voltage of the tested apparatus with the tested apparatus in circuit. The measuring gap should then be greatly lengthened out and the voltage increased until the tested apparatus arcs over. This arc-over voltage should then be determined by multiplying the voltmeter reading by the equivalent ratio found above. Direct measurement of the spark-over voltage over one gap by another gap should always be avoided.

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The values in Table 203 refer to a relative humidity of 80 per cent. Variations from this humidity may involve appreciable variations in the sparking distance.

2366. Sphere spark-gap. The standard sphere spark-gap shall be between two suitably mounted spheres. No extraneous body, or external object of the circuit, shall be nearer the spheres than twice their diameter. The shanks shall be not greater in diameter than one-fifth the sphere diameter. Metal collars, etc., through which the shanks extend, shall be as small as practicable and shall not, during any measurement, come closer to the sphere than the maximum gap length used in the measurement. The sphere diameter should not vary more than 0.1 per cent., and the curvature measured by a spherometer, should not vary more than 1 per cent. from that of a true sphere of the required diameter.

†**2367. Use of spherometer.** In using the spherometer to measure curvature, the distance between the points of contact of the spherometer shall be within the limits as indicated in Table 203.

Table 203. Spherometer specifications

Diameter of sphere in millimeters	Distance between contact points in millimeters	
	Maximum	Minimum
62.5	35	25
125	45	35
250	65	45
500	100	65

2368. Sphere-gap sparking distances. The sparking distance between spheres for various root-mean-square sinusoidal voltages shall be assumed to be as shown in Table 204.

‡**2369. Correction of gap spacing for air density.** The spacing at which it is necessary to set a gap to spark over at some required voltage is found as follows. Divide the required voltage by the correction factor given in Table 205 and use the new voltage thus obtained, to find the corresponding spacing from Table 204, using a graph of the latter, if more convenient.

‡**2370. Correction of voltage for air density.** The voltage at which

* When used as specified, the accuracy obtainable should be approximately 3 per cent.

† In using sphere gaps constructed as indicated in Pars. 2366 and 2367, it is assumed that the apparatus will be set up for use in a space comparatively free from external dielectric fields. Care should be taken that conducting bodies forming part of the circuit, or at circuit potential, are not so located with reference to the gap that their dielectric fields are superposed on the gap, *e.g.*, the protecting resistance should not be arranged so as to present large masses or surfaces near the gap, even at a distance of two sphere diameters.

In case the sphere is grounded, the spark point of the grounded sphere should be approximately five diameters above the floor or ground.

‡ Effect of air density on spark-over voltage. The spark-over voltage, for a given gap, decreases with decreasing barometric pressure and increasing temperature. This variation may be considerable at high altitudes. When the variation from sea level is not great, the relative air density may be used as the correction factor; when the variation is great, or greater accuracy is desired, the correction factor corresponding to the relative air density should be taken from Table 204 in which

$$\text{Relative air density} = \frac{0.392b}{273 + t}$$

b = barometric pressure in millimeters

t = temperature in deg. cent.

Corrected curves may be plotted for any given altitude, if desired. It will be noted in Table 213 that for values of relative air density above 0.9 the correction factor does not differ greatly from the relative air density.

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gap sparks over is derived from the voltage corresponding to the spacing Table 204 by multiplying by the correction factor.

Table 204. Sphere-gap spark-over voltages

(At 25 deg. cent. and 760 mm. barometric pressure)

Kilovolts	Sparking distance in millimeters							
	62.5 mm. spheres		125 mm. spheres		250 mm. spheres		500 mm. spheres	
	One sphere grounded	Both spheres insulated	One sphere grounded	Both spheres insulated	One sphere grounded	Both spheres insulated	One sphere grounded	Both spheres insulated
10	4.2	4.2	.....	.....	.....	.....	.....	.....
20	8.6	8.6	.....	.....	.....	.....	.....	.....
30	14.1	14.1	14.1	14.1	.....	.....	.....	.....
40	19.2	19.2	19.1	19.1	.....	.....	.....	.....
50	25.5	25.0	24.4	24.4	.....	.....	.....	.....
60	34.5	32.0	30	30	29	29	.....	.....
70	46.0	39.5	36	36	35	35	.....	.....
80	62.0	49.0	42	42	41	41	41	41
90	.....	60.5	49	49	46	45	46	45
100	.....	.....	56	55	52	51	52	51
120	.....	.....	79.7	71	64	63	63	62
140	.....	.....	108	88	78	77	74	73
160	.....	.....	150	110	92	90	85	83
180	.....	.....	.....	138	109	106	97	95
200	.....	.....	.....	.....	128	123	108	106
220	.....	.....	.....	.....	150	141	120	117
240	.....	.....	.....	.....	177	160	133	130
260	.....	.....	.....	.....	210	180	148	144
280	.....	.....	.....	.....	250	203	163	158
300	.....	.....	.....	.....	.....	231	177	171
320	.....	.....	.....	.....	.....	265	194	187
340	.....	.....	.....	.....	.....	.....	214	204
360	.....	.....	.....	.....	.....	.....	234	221
380	.....	.....	.....	.....	.....	.....	255	239
400	.....	.....	.....	.....	.....	.....	276	257

The sphere-gap is more sensitive than the needle-gap to momentary rise voltage and the voltage required to spark over the gap should be obtained slowly closing the gap under constant voltage, or by slowly raising the ltage with a fixed setting of the gap. Open arcs should not be permitted proximity to the gap during its operation, as they may affect its calibration.

Table 205. Air density corr

Relative air density	Diameter of s	
	62.5	1
0.50	0.547	0.
0.55	0.594	0
0.60	0.640	0
0.65	0.686	0
0.70	.732	0
0.75	0.777	0
0.80	0.821	0
0.85	0.866	0
0.90	0.910	0
0.95	0.956	0
1.00	1.000	1
1.05	1.044	1
1.10	1.090	1

Insulatio

2280. General. The insulation circuits of equal voltage above gr groups of circuits of different voltage

2281. Voltage for insulation tests shall, if possible, be made at since the insulation resistance varie if a pressure other than 500 volts is pressure shall be clearly specified.

2282. Minimum values. The operating temperature shall be not formula:

Insulation resistance in meg

The formula applies only to dry attainable in oil-immersed apparatus

Reg

2300. Conditions for tests of The regulation of generators shall that of alternating-current machines

(b) *Wave form:* A sine wave of vo the regulation of alternating-curren except where expressly specified othe

* The order of magnitude obtaine table.

Table 206. Insulation resistance app

Rated voltage of machine	100 kv-a.
100	0.091
1,000	0.91
10,000	9.1
100,000	.....

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Table 205. Air density correction factors for sphere-gaps

Relative ir density	Diameter of standard spheres in millimeters			
	62.5	125	250	500
0.50	0.547	0.535	0.527	0.519
0.55	0.594	0.583	0.575	0.567
0.60	0.640	0.630	0.623	0.615
0.65	0.686	0.677	0.670	0.663
0.70	.732	0.724	0.718	0.711
0.75	0.777	0.771	0.766	0.759
0.80	0.821	0.816	0.812	0.807
0.85	0.866	0.862	0.859	0.855
0.90	0.910	0.908	0.906	0.904
0.95	0.956	0.955	0.954	0.952
1.00	1.000	1.000	1.000	1.000
1.05	1.044	1.045	1.046	1.048
1.10	1.090	1.092	1.094	1.096

Insulation Resistance

2380. General. The insulation resistance test shall be made with all uits of equal voltage above ground connected together. Circuits or ups of circuits of different voltage above ground shall be tested separately.

2381. Voltage for insulation resistance test. Insulation resistance s shall, if possible, be made at a direct-current pressure of 500 volts. ce the insulation resistance varies with the pressure, it is necessary that, pressure other than 500 volts is to be employed in any case, this other ssure shall be clearly specified.

2382. Minimum values. The insulation resistance of a machine at its rating temperature shall be not less than that given by the following mula:

$$\text{Insulation resistance in megohms} = \frac{\text{voltage at terminals}}{\text{rating in kv-a.} + 1{,}000}$$

The formula applies only to dry apparatus. Such high values are not ainable in oil-immersed apparatus.

Regulation

2390. Conditions for tests of regulation. (*a*) *Speed and frequency:* e regulation of generators shall be determined at constant speed, and t of alternating-current machines at constant frequency.
(*b*) *Wave form:* A sine wave of voltage shall be assumed in determining regulation of alternating-current machinery receiving electric power, ept where expressly specified otherwise. (See Par. **2340.**)

The order of magnitude obtained by this rule is shown in the following le.

ble 206. Insulation resistance of machines excluding oil-immersed apparatus

Rated voltage of machine	Megohms		
	100 kv-a.	1,000 kv-a.	10,000 kv-a.
100	0.091	0.05	.....
1,000	0.91	0.50	0.091
10,000	9.1	5.0	0.91
100,000	.....	50	9.1

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(c) *Temperature:* It is desirable that all parts of the machine affecting the regulation be maintained at constant temperature between the two loads and where the influence of temperature is of consequence, a reference temperature of 75 deg. cent. shall be considered as standard. If change of temperature should occur during the tests the results shall be corrected to the reference temperature of 75 deg. cent.

CONSTRUCTION

Rating Plates

2401. Marking of rating plate. (a) *Distinctive marking:* It is recommended that the rating plate of machines which comply with the Institute Rules shall carry a distinctive special sign, such as "A. I. E. E. 1920 Rating" or "A20" rating.

(b) *Significance of marking:* The absence of any statement to the contrary on the rating plate of a machine implies that it is intended for continuous service and for the standard altitude and ambient temperature. (See Pars. **2211**, **2212**, **2215**, and **2220**.)

(c) *Marking for various ratings:* The rating plate of a machine intended to work under various kinds of rating must carry the necessary information in regard to those kinds of ratings.

CHAPTER III

GENERAL DEFINITIONS

In this chapter are given definitions which are of general application to electric circuits, machines and systems. Definitions pertaining to a specific class of apparatus are given in the chapter on the class of apparatus in question. The definitions here given are primarily descriptive rather than scientifically precise.

The definitions given below for currents are also applicable, in most cases, to electromotive forces, potential differences, magnetic fluxes, etc.

DEFINITIONS

General

3000. Ambient temperature. The ambient temperature is the temperature of the air or water which comes into contact with the heated parts of a machine and carries off its heat. See Pars. **2300** and **2301**.

Resistivity

3020. Resistivity. The resistivity of a material is the resistance expressed in ohms between two opposite faces of a centimeter cube of the material, and is usually coupled with a statement of the temperature. (See Par. **9050**.)

Apparatus

3064. Resistor. A resistor is a device used primarily because it possesses the property of electrical resistance. Resistors are used in electric circuits for purposes of operation, protection, or control. See Par. **7016**.

3070. Inductor. An inductor is a device used primarily because it possesses the property of inductance.

3078. Reactor. A reactor is a device used primarily because it possesses the property of reactance. Reactors are used in electric circuits for purposes of operation, protection or control.

Kinds of Currents

3104. Direct current. A direct current is a unidirectional current. As ordinarily used, the term designates a practically non-pulsating current.

3108. Pulsating current. A pulsating current is a current which has regularly recurring variations in magnitude. As ordinarily employed the term refers to a unidirectional current.

3112. Continuous current. A continuous current is a practically non-pulsating direct current.

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116. Alternating current. An alternating current is a current the ection of which reverses at regularly recurring intervals. Unless dis- tly otherwise specified, the term *alternating current* refers to a periodically ying current with successive half waves of the same shape and area. e Par. **3212.**)

120. Oscillating, or free alternating current. An oscillating, or free rnating current is the current following any electro-magnetic disturb- e in a circuit having capacity, inductance, and less than the critical stance. When the critical resistance of a circuit is reached the current omes aperiodic.

Alternating Currents

204. Cycle. A cycle is one complete set of positive and negative ues of an alternating current.

206. Period. The period of an alternating current is the time required the current to pass through one cycle.

208. Frequency. The frequency of an alternating current is the num- of cycles through which it passes per second, that is, the reciprocal of period.

212. Wave Shape. The wave shape, or wave form, of an alternating rent is the shape of the curve obtained when the instantaneous values he current are plotted against time in rectangular co-ordinates. wo alternating quantities are said to have the same wave shape when ir ordinates of corresponding phase bear a constant ratio to each other. e wave shape, as thus understood, is therefore independent of the fre- ncy of the current and of the scale to which the curve is plotted.

214. Sine-wave, or simple alternating current. A sine wave, or ple alternating current is a current whose wave shape is sinusoidal.

3213. Root-mean-square or effective value. The root-mean-square effective value of an alternating current is the square root of the mean he squares of the instantaneous values for one complete cycle. It is ally abbreviated r.m.s. Unless otherwise sepcified, the numerical ue of an alternating current refers to its r.m.s. value. The word "vir- l" is sometimes used in place of r.m.s., particularly in Great Britain.

222. Phase. Phase is the fraction of the period of an alternating cur- t which has elasped since the current passed through the zero position eference.

his fraction is usually expressed in angular measure, and the period cor- ponding to one complete cycle is taken as representing 2π radians or 360 rees. The angles are frequently called electric angles, and the degrees tric degrees.

n the usual equation

$$i = I_m \sin(\omega t + \varphi)$$

quantity $(\omega t + \varphi)$ is the phase and φ is the phase angle of the current.

3224. Phase difference; lead and lag. The phase difference of two rnating quantities of the same frequency is the difference between their ues at any instant. That quantity whose maximum occurs first in time aid to lead the other, and the latter is said to lag behind the former.

228. Vector representation and angular velocity. A sine-wave cur- t or voltage may be represented by a vector of constant length rotating nter-clockwise at a constant angular velocity ($\omega = 2\pi f$); this angular ocity is frequently termed the angular velocity of the current or voltage.

3230. Counter-clockwise convention. It is recommended that, in

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The r.m.s. value of a sine wave (see Par. **3214**) is equal to its maximum, rest value, divided by $\sqrt{2}$.

When the two alternating quantities do not have the same wave form, phase difference as here defined may not be identical with equivalent se difference as defined in Par. **3262.**

See Publication 12 of the International Electrotechnical Commission port of Turin meeting, September, 1911, p. 78).

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any vector diagram, the leading vector be drawn counter-clockwise with respect to the lagging vector, as in Fig. 3—1 where *OI* represents the vector of a current in a simple alternating-current circuit lagging behind the vector *OE* of impressed electromotive force.

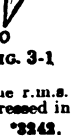


FIG. 3-1

3234. Power. Power is the rate of transfer of energy. In case of an alternating-current circuit the word power is generally used to denote the average value of the power over a cycle. The power in an electric circuit at any instant is equal to the product of the values of the current and voltage at that instant and is generally called the instantaneous power.

3238. Apparent power or volt-amperes. The apparent power, or volt-amperes, in an alternating-current circuit is the product of the r.m.s. value of the voltage across the circuit and the r.m.s. value of the current in the circuit. Apparent power is also expressed in kilovolt-amperes, abbreviated kv-a.

*3242. **Power factor.** Power factor is the ratio of the power to the apparent power.

†3246. **Reactive volt-amperes.** The reactive volt-amperes in a circuit is the square root of the difference between the square of the apparent power and the square of the power.

‡3250. **Reactive factor.** The reactive factor is the ratio of the reactive volt-amperes to the total volt-amperes.

§3254. **Active component.** The active component of the current in a circuit is the average power divided by the voltage.

‖3256. **Reactive component.** The reactive component of the current in a circuit is the square root of the difference between the square of the current and the square of the active component of the current.

3260. **Equivalent sine wave.** An equivalent sine wave is a sine wave which has the same frequency and the same r.m.s. value as the actual wave.

3262. **Equivalent phase difference.** The equivalent phase difference (applicable to non-sinusoidal currents and voltages) is the phase difference between the equivalent sine waves of current and voltage when so related as to have the same power factor as the non-sinusoidal quantities.

There are cases, however, where this equivalent phase difference is misleading, since the presence of harmonics in the voltage wave, current wave or in both, may reduce the power factor without producing a corresponding displacement of the two wave forms with respect to each other; *e.g.*, the case of an a-c. arc. In such cases, the components of the equivalent sine waves, the equivalent reactive factor and the equivalent reactive volt-amperes may have no physical significance.

¶3266. **Crest factor or peak factor.** The crest factor or peak factor of a wave is the ratio of the crest, or maximum, value to the r.m.s. value.

---

* The power factor when both the current and voltage are sinusoidal is equal to the cosine of the angle which expresses their difference in phase (see Par. 3224).

† The reactive volt-amperes, when both current and voltage are sinusoidal, is equal to the volt-amperes times the sine of the angle which expresses the phase difference between current and voltage.

‡ The reactive factor, when both current and voltage are sinusoidal, is equal to the sine of the angle which expresses their phase difference.

§ The active, or in-phase, component of the current in a circuit corresponds to average power passing in a given direction through the circuit. With sine wave voltage and current, the active component of the current is in phase with the voltage.

‖ The reactive, or quadrature, component of the current in a circuit corresponds to power alternating in direction in the circuit so that the average value of the power transferred in a given direction through a cycle is zero. With sine wave current and voltage the reactive component of the current is in quadrature with the voltage.

¶ The crest factor of a sine wave is $\sqrt{2}$.

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*3270. **Form factor of a wave.** The form factor of a wave is the ratio the r.m.s. to the algebraic mean ordinate taken over a half cycle beginning with the zero value. If the wave passes through zero more than twice during a single cycle, that zero shall be taken which gives the largest algebraic mean for the succeeding half-cycle.

3274. **Deviation factor of a wave.** The deviation factor of a wave is the ratio of the maximum difference between corresponding ordinates of the wave and of the equivalent sine wave to the maximum ordinate of the equivalent sine wave when the waves are superposed in such a way as to make this maximum difference as small as possible.

3278. **Telephone interference factor of a wave.** (See Par. 4352.) The telephone interference factor is the ratio of the square root of the sum of the squares of the weighted values of all the sine wave components (including in alternating waves both fundamental and harmonics) to the r.m.s. value of the wave.

Circuits and Phases

3304. **Electric circuit.** An electric circuit is a path in which an electric current may flow. Strictly speaking, an electric circuit is a complete circuitory path, but the term circuit is commonly employed to designate a specific part of a complete path. When part of a complete path is referred to, such as a branch circuit, a derived circuit, or a conductor, both the terminals and the conductor which form that path should be specified in order to avoid ambiguity; *e.g.*, the circuit *a-b-c*. When the whole circuit is referred to, it may be designated as a complete or closed circuit.

†3324. **Single-phase circuit.** A single-phase circuit is a circuit energized by a single alternating electromotive force.

‡3328. **Three-phase circuit.** A three-phase circuit is a combination of circuits energized by alternating electromotive forces which differ in phase by one-third of a cycle; *i.e.*, 120 degrees.

§3328. **Quarter-phase or two-phase circuit.** A quarter-phase or two-phase circuit is a combination of circuits energized by alternating electromotive forces which differ in phase by a quarter of a cycle; *i.e.*, 90 degrees.

‖3330. **Six-phase circuit.** A six-phase circuit is a combination of circuits energized by alternating electromotive forces which differ in phase by one-sixth of a cycle; *i.e.*, 60 degrees.

3332. **Polyphase circuit.** A polyphase circuit is a circuit of more than single phase. This term is ordinarily applied to symmetrical systems.

3344. **Symmetrical voltages and currents.** Polyphase voltages or currents are symmetrical when the voltages or currents have the same wave shape and r.m.s. value and differ in phase each from the next by the same angle.

3348. **Symmetrical polyphase system.** A symmetrical polyphase system is a polyphase system in which the voltages are symmetrical.

¶3352. **Balanced polyphase system.** A balanced polyphase system is a polyphase system in which both the currents and voltages are symmetrical.

Loads

3404. **Reactive load.** A reactive load is a load in which the current lags behind or leads the voltage across the load.

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* The form factor of a sine wave is $\frac{\pi}{2\sqrt{2}}$ or 1.11.

† A single-phase circuit is usually supplied through two wires. The currents in these two wires, counted outward from the source, differ in phase by 180 deg. or a half cycle.

‡ In practice the phases may vary several degrees from the specified angle.

§ In practice the phases may vary several degrees from the specified angle.

‖ In practice the phases may vary several degrees from the specified angle.

¶ The term balanced polyphase system is applied also to a quarter-phase (or two-phase) system in which the voltages have the same wave form and r.m.s. value and in which the currents have the same wave form and r.m.s. value and differ in phase by 90 electrical degrees.

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3406. Non-reactive load. A non-reactive load is a load in which the current is in phase with the voltage across the load. (The term non-inductive load is sometimes used for non-reactive load.)

3408. Inductive load. An inductive load is a reactive load in which the current lags behind the voltage across the load.

3410. Condensive load. A condensive load is a reactive load in which the current leads the voltage across the load.

*__3414. Balanced polyphase load.__ A balanced polyphase load is a load to which symmetrical currents are supplied when it is connected to a system having symmetrical voltages.

3424. Connected load. The connected load on any system, or part of a system, is the combined continuous rating of all the receiving apparatus on consumers' premises which is connected to the system, or part of the system under consideration.

3434. Peak power. The peak power is the average power during a time interval of specified duration occurring within a given period of time, that interval being selected during which the average power is greatest.

3438. Load factor. The load factor is the ratio of the average power to the peak power.

In each case, the interval of maximum load and the period over which the average is taken should be definitely specified, such as a "half-hour monthly" load factor. The proper interval and period are usually dependent upon local conditions and upon the purpose for which the load factor is to be used.

3442. Plant factor. The plant factor is the ratio of the average load to the rated capacity of the power plant; *i.e.*, to the aggregate ratings of the generators.

3454. Demand of an installation or system. The demand of an installation or system is the load which is drawn from the source of supply at the receiving terminals averaged over a suitable and specified interval of time. Demand is expressed in kilowatts, kilovolt-amperes, amperes, or other suitable units.

3458. Maximum demand. The maximum demand of an installation or system is the greatest of all the demands which have occurred during a given period. It is determined by measurement, according to specifications, over a prescribed time interval.

3460. Demand factor. The demand factor of any system, or part of a system, is the ratio of the maximum demand of the system, or part of a system, to the total connected load of the system, or of the part of the system under consideration.

3464. Diversity factor. The diversity factor of any system, or part of a system, is the ratio of the sum of the maximum power demands of the subdivisions of the system, or part of a system, to the maximum demand of the whole system, or part of the system under consideration, measured at the point of supply.

Machinery and Apparatus

3504. Capacity (or, properly, capability). The word "capacity" is frequently used in the general sense of "capability." It is also used in a more exact sense to denote the load which, when carried by a machine, apparatus, or device will, under specified conditions of test, cause it to reach *any one of its physical limitations*, such, for example, as operating temperature or ability to maintain required voltage.

Capacity should be distinguished from rating. On account of the different senses in which it has been employed (see Par. **3508**), capacity is less used than it formerly was, rating being more useful commercially.

* The term balanced polyphase load is applied also to a load to which are supplied two currents having the same wave form and r.m.s. value and differing in phase by 90 electrical degrees when it is connected to a quarter-phase (or two-phase) system having voltages of the same wave form and r.m.s. value.

*__3508. Rating.__ A rating of a
tracy designation of an operating
(The rating of a machine is th
shall be based on, but shall not
taken from the machine under p
called the rated output. *Maxi
with capability as defined* in Par.

3514. Efficiency. The efficie
the ratio of its useful output to i
the above output and input sha
input respectively.

†__3524. Conventional efficie__
electric machine or apparatus is
output and the losses, or of the
in either case conventional value

3534. Plant, or system, effi
ratio of the energy delivered fro
by it in a specified period of time
it may be desirable to calculat
part of the system, at the act
during the specified interval.
from the losses at 75 deg. cent.,
ture of reference for all efficien
cable to storage batteries. (Se

3535. Regulation. The reg
acteristic quantity (such as ter
quantity occurring between an
two loads considered shall be a
ture attained under normal op
by stating the numerical value
be expressed by the "percenta
of the change in the quantity
of the quantity at either one
The normal value may be eith
induction motors; or it may
a-c. generators.

It is assumed that all parts
tain constant temperature be
of temperature is of conseque
shall be considered as standar

* The term maximum loa
mechanical, commutation, or

† The need for assigning co
the fact that some of the los
terminable, and must, in man
method of test, or else values
"conventional" values shall
ventional efficiency."

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3604. Table 301. Symbols and abbreviations

Name of quantity	Symbol for the quantity	Unit	Abbreviation for the unit
Acceleration due to gravity	g	centimeter per second per second	cm. per sec. per sec.
Admittance	Y, y	mho	
Angular velocity	ω	radian per second	
Capacitance (electrostatic capacity)	C	farad	
Conductance	g	mho	
Conductivity	γ	*mho per centimeter	mho per cm.
Current	I, i	ampere	
Dielectric constant	K		
Efficiency	η	per cent.	
Electromotive force, abbreviated e.m.f.	E, e	volt	
Electrostatic field intensity	F		
Electrostatic flux	Ψ		
Electrostatic flux density	D		
Energy, in general	U or W	joule, watt-hour	
Frequency	f	cycle per second	~
Impedance	Z, z	ohm	
Inductance (or coefficient of self induction)	L	henry	
Intensity of magnetization	J		
Length	l	centimeter	cm.
Magnetic field intensity	H, $\mathfrak{H}$	gilbert per centimeter or gauss*	gilbert per cm.
Magnetic flux	Φ, φ	maxwell	
Magnetic flux density	B, $\mathfrak{B}$	gauss	
Magnetomotive force, abbreviated m.m.f.	$\mathfrak{F}$	gilbert*	
Mass	m	gram	g
Mutual inductance (or coefficient of mutual induction)	M	henry	
Number of conductors or turns	N	convolution or turn of wire	
Permeability	$\mu = B/H$		
Phase displacement	θ, φ	degree or radian	°
Potential difference, abbreviated p.d.	V, v or E, e	volt	
Power	P, p	watt	
Quantity of electricity	Q, q	coulomb, ampere-hour	

* The gauss is provisionally accepted for the present as the name of both the unit of field intensity and flux density, on the assumption that permeability is a simple numeric.

An additional unit for magnetomotive force is the "ampere-turn," for flux the "line," for magnetic flux density "maxwells per sq. in."

The numerical values of resistivity and conductivity are *ohms resistance* and *mhos conductance* between two opposite faces of a cm. cube of the material in question, but the correct names are as given, not ohms and mhos per cm. cube, as commonly stated.

The value 980.665 for g_o has been the accepted standard value for many years and was formerly considered to correspond accurately to 45 deg. latitude and sea level. Later researches, however, have shown that the most reliable value for 45 deg. and sea-level is slightly different; but this does not affect the standard value given above.

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Name of quantity	Symbol for the quantity	Unit	Abbreviation for the unit
Reactance	X, x	ohm	.....
Reluctance	$\mathfrak{R}$	.....	.....
Resistance	R, r	ohm	.....
Resistivity	ρ	*ohm-centimeter	ohm-cm.
Standard acceleration due to gravity (at about 45 deg. latitude and sea level) equals 980,665*	g_n	centimeter per second per second	cm. per sec. per sec.
Susceptance	b	mho	.....
Susceptibility	$\kappa = J/H$	.....	.....
Temperature	θ	degree centigrade	°C.
Time	t	second	sec.
Velocity of rotation	n	revolution per second	rev. per sec.
Voltage	E, e or V, v	volt	.....

*See footnotes on previous page.

3606. Symbols for maximum, instantaneous and r.m.s. values. I_m, I_m and P_m should be used for maximum cyclic values, e, i and p for instantaneous values, E and I for r.m.s. values (see Par. 3218) and P for the average value of the power, or the active power. These distinctions are not necessary in dealing with direct-current circuits. In print, vector quantities should be represented by bold-face capitals.

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CHAPTER IV

STANDARDS FOR ROTATING MACHINES (OTHER THAN RAILWAY MOTORS, RAILWAY SUBSTATION MACHINERY CARRYING TRACTION LOADS, AND AUTOMOBILE PROPULSION MACHINES)

The A. I. E. E. Standards for rotating machines are the general standards shown in Chapters II and III and the standards in other chapters which are applicable to the devices involved, together with the modifications and extensions given in this chapter.

DEFINITIONS

General

Certain rules applying exclusively to railway machinery have, for convenience, been placed in Chapter V, with cross references in all cases in this chapter. The rules of Chapter IV apply to railway machinery except as they are modified by rules of Chapter V.

4000. Classification of electric rotating machinery. Rotating electric machinery may be classified in various ways, these classifications overlapping or interlocking in considerable degree. *First*, Rotating electric machinery may be classified as direct-current and alternating-current; *second*, according to the function of the machines; *e.g.*, motors, generators, boosters, motor-generators, dynamotors, double-current generators, converters and phase advancers; *third*, according to construction or principle of operation; *e.g.*, commutating, synchronous, induction, unipolar, rectifying. Obviously, some of these machines could be rationally included in either classification, *e.g.*, motor-generators and rectifying machines. In the following, self-evident definitions have for the most part been omitted.

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Functional Classification of Rotating Electric Machines

4001. Generator. A generator is a machine which transforms mechanical power into electric power.

4002. Motor. A motor is a machine which transforms electric power into mechanical power.

4003. Booster. A booster is a generator inserted in series in a circuit to change its voltage. A booster may be driven by an electric motor (in which case it is termed a motor-booster) or otherwise.

4004. Motor-generator set. A motor-generator set is a transforming device consisting of one or more motors mechanically coupled to one or more generators.

4005. Dynamotor. A dynamotor is a transforming device combining both motor and generator action in one magnetic field, either with two armatures, or with one armature having two separate windings and independent commutators.

4006. Direct-current compensator or balancer. A direct-current compensator or balancer is a machine which comprises two or more similar direct-current machines (usually with shunt or compound excitation) directly coupled to each other and connected in series across the outer conductors of a multiple-wire system of distribution, for the purpose of maintaining the potentials of the intermediate wires of the system, which are connected to the junction points between the machines.

4007. Double-current generator. A double-current generator is a machine which supplies both direct and alternating currents from the same armature winding.

4008. Converter. A converter is a machine which employs mechanical rotation in changing electric energy from one form into another. There are several types of converters, as defined in Pars. **4009** to **4013** below.

4009. Direct-current converter. A direct-current converter is a machine which converts from a direct current to a direct current, usually with a change of voltage. Such a machine may be either a motor-generator set or a dynamotor.

4010. Synchronous converter. A synchronous converter (sometimes called a rotary converter) is a machine which converts from an alternating to a direct current, or vice-versa. It is a synchronous machine with a single closed-coil armature winding, a commutator and slip rings.

4011. Cascade converter. A cascade converter (also called a motor converter) is a combination of an induction motor with a synchronous converter, the secondary circuit of the former feeding directly into the armature of the latter; *i.e.*, a synchronous converter concatenated with an induction motor.

4012. Frequency converter. A frequency converter is a machine which converts the power of an alternating-current system from one frequency to another, with or without a change in the number of phases, or in the voltage.

4013. Rotary phase-converter. A rotary phase-converter is a machine which converts from an alternating-current system of one or more phases to an alternating-current system of a different number of phases, but of the same frequency.

4014. Phase advancer. A phase advancer is a machine which supplies reactive volt-amperes to the system to which it is connected. Phase advancers may be either synchronous or asynchronous.

4015. Synchronous condenser or synchronous phase advancer. A synchronous condenser or synchronous phase advancer is a synchronous machine, running either idle or with load, the field excitation of which may be varied so as to modify the power factor of the system, or through such modification to influence the load voltage.

Constructional Classification of Rotating Electric Machines

4016. Direct-current commutating machines. A direct-current commutating machine comprises a magnetic field of constant polarity, an armature, and a commutator connected therewith. Specific types of direct-

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urrent commutating machines are: Direct-current generators; direct-urrent motors; direct-current boosters; direct-current motor-generator sets nd dynamotors; direct-current compensators or balancers; and arc machines.

4017. Alternating-current commutating machine. An alternating-urrent commutating machine comprises a magnetic field of alternating olarity, an armature, and commutator connected therewith. (See Pars. 071 to 4074.)

4018. Synchronous commutating machine. Synchronous commu-ating machines include synchronous converters, cascade converters, and louble-current generators.

4019. Synchronous machine. A synchronous machine comprises a onstant magnetic field and an armature receiving or delivering alternating urrents in synchronism with the motion of the machine; *i.e.*, having a requency strictly proportional to the speed of the machine. Specific types f synchronous machines are defined in Pars. 4020 to 4023 below.

4020. Alternator. An alternator is a synchronous alternating-current enerator, either single-phase or polyphase.

4021. Polyphase alternator. A polyphase alternator is a polyphase ynchronous alternating-current generator, as distinguished from a single-hase alternator.

4022. Inductor alternator. An inductor alternator is an alternator in hich both field and armature windings are stationary, and in which masses f iron or inductors, by moving past the coils, alter the magnetic flux through hem. It may be either single-phase or polyphase.

4023. Synchronous motor. A synchronous motor is a machine struc urally identical with an alternator, but operated as a motor.

4024. Induction machine. An induction machine is a machine wherein rimary and secondary windings rotate with respect to each other; *e.g.*, nduction motors, induction generators, certain types of frequency converters nd certain types of rotary phase converters.

4025. Induction motor. An induction motor is an alternating-current notor, either single-phase or polyphase, comprising independent primary nd secondary windings, one of which, usually the secondary, is on the rotat-ng member. The secondary winding receives power from the primary by lectromagnetic induction.

4026. Induction generator. An induction generator is a machine tructurally identical with an induction motor, but driven above synchron-us speed as an alternating-current generator.

4027. Engine type generator. An engine type generator is one coupled o an engine in such a way that it cannot be run independently of the engine.

4028. Unipolar or acyclic machine. A unipolar, or acyclic machine, s a direct-current machine, in which the voltage generated in the active onductors maintains the same direction with respect to those conductors.

Speed Classification of Motors

4035. Constant-speed motor. A constant-speed motor is one whose peed is either constant or does not materially vary; such as a synchronous notor, an induction motor with small slip, and an ordinary direct-current hunt motor.

4036. Multi-speed motor (or change-speed motor). A multi-speed notor is a motor which can be operated at any one of several distinct speeds these speeds being practically independent of the load), but which cannot e operated at intermediate speeds.

4037. Adjustable-speed motor. An adjustable-speed motor is one in hich the speed can be varied gradually over a considerable range, but when nce adjusted remains practically unaffected by the load; such as a shunt notor designed for a considerable range of speed variation.

4038. Base speed of an adjustable-speed motor. The base speed of n adjustable-speed motor is that speed of the motor obtained with full eld under full load with no resistor in the armature circuit.

4039. Varying-speed motor. A varying-speed motor is one whose peed varies with the load, ordinarily decreasing when the load increases;

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such as a series motor, a compound-wound motor, and a series-shunt motor. As a subclass of varying-speed motors may be cited adjustable varying-speed motors, or motors in which the speed can be varied over a considerable range at any given load, but when once adjusted varies with the load; *e.g.*, compound-wound motors arranged for adjustment of speed by varying the strength of the shunt field.

Classification of Rotating Electric Machines Relative to their Degree of Enclosure

4041. Open machine. An open machine is of either the pedestal-bearing or end-bracket type where there is no restriction to ventilation other than that necessitated by good mechanical construction.

4042. Protected machine. A protected machine is one in which the armature, field coils, and other live parts are protected mechanically from accidental or careless contact, while free ventilation is not materially obstructed.

4043. Enclosed ventilated machine. An enclosed ventilated (or semi-enclosed) machine is one in which the ventilating openings in the frame are protected with wire screen, expanded metal, or other suitable perforated covers, having apertures not exceeding 12 sq. in. (3.2 sq. cm.) in area. (See Par. 4316.)

4044. Totally enclosed machine. A totally enclosed machine is one so enclosed as to prevent circulation of air between the inside and the outside of the case, but not sufficiently to be termed air-tight.

4045. Separately ventilated machine. A separately ventilated machine has its ventilating air supplied by an independent fan or blower external to the machine.

4046. Self-ventilated machine. A self-ventilated machine differs from a separately ventilated machine only in having its ventilating air circulated by a fan, blower, or centrifugal device integral with the machine.

If the heated air expelled from the machine is conveyed away through a pipe attached to the machine, this should be so stated.

4047. Water-cooled machine. A water-cooled machine is one which mainly depends on water circulation for the removal of its heat.

4048. Drip-proof machine. A drip-proof machine is one so protected as to exclude falling moisture or dirt. A drip-proof machine may be either open or semi-enclosed, if it is provided with suitable protection integral with the machine, or so enclosed as to exclude effectively falling solid or liquid material.

4051. Explosion-proof machine (or flame-proof machine). An explosion-proof machine is a machine in which the enclosing case can withstand, without injury, any explosion of gas that may occur within it, and will not transmit the flame to any inflammable gas outside it.

4052. Machine with explosion-proof slip-ring enclosure. A machine in which the slip rings and brushes alone are included within an explosion-proof case should not be described as an explosion-proof machine, but as a machine with explosion-proof slip-ring enclosure.

Classification of Alternating-current Commutator Motors

(An alternating-current commutator motor may be classified under more than one of the following groups)

Classification by phases of energy supply

4061. Single-phase commutator motor. A single-phase commutator motor is one that receives the whole of its energy from only one phase of an alternating-current supply system, without requiring external phase-converting apparatus.

4062. Polyphase commutator motor. A polyphase commutator motor is one that receives its energy from a plurality of phases of an alternating-current sypply system, or from a single-phase system through phase-converting apparatus external to the motor.

Classification by S

4063. General. For convenience tors may be classified with reference constant-speed motors, (2) multi-spee and (4) varying-speed motors. Defi 4035 to 4039 for motors in general, sh commutator motors, in so far as they

Classification

4064. Stator-excited commutat tator motor is one in which the torque a winding located on the stator. By that component of the magnetic field of the current, produces the torque of

4065. Rotor-excited commutato tator motor is one in which the torqu is a winding located on the rotor. (S

4066. Stator- and rotor-excited c rotor-excited commutator motor is one is due to currents in windings located Par. 4064.)

***4067. Constant-field commutato** tator motor is one in which the torque constant, independent of the load. (See

†4068. Varying-field commutator tator motor is one in which the torque portion with the current in the armature (See Par. 4064.)

Classification by Neutraliza

4069. Neutralized commutator m motor is one in which use is made of a w force which at each instant and at each face is practically equal and opposite to armature current.

4070. Compensated commutator tator motor is one in which means, othe provided within the motor for improvin

Classification by En

4071. Conduction commutator m motor is one in which the working ener members, and is conveyed to it by cond meant the energy which is directly conv which includes the shaft energy output p

4072. Transformer commutator m motor is one in which the working energy to the other by transformer action.

A motor in which the energy required b the rotor) is conveyed to it by electrom action may properly be referred to either "transformer motor." Although it is equ a commutator, the term "induction moto without a commutator. The term "tra therefore recommended for use with motor type having commutators.

* Alternating-current commutator motor load-speed characteristics similar to those o but not all alternating-current commutato characteristics are constant-field machines.

† Such a motor will in general have loa those of the direct-current series motor.

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4073. Transformer-conduction commutator motor. A transformer-conduction commutator motor is one in which the energy required by its armature (which is generally the rotor) is conveyed to it by both conduction and electromagnetic induction.

4074. Repulsion commutator motor. A repulsion commutator motor is a transformer commutator motor in which use is made of brushes for short-circuiting a number of coils of the commutated winding.

Miscellaneous Definitions

4085. Saturation factor. The saturation factor of a machine is the ratio of a small percentage increase in field excitation to the corresponding percentage increase in voltage thereby produced. Unless otherwise specified, the saturation factor of a machine refers to the no-load excitation required at normal rated speed and voltage. It is determined from measurements of saturation made on open circuit at rated speed.

4086. Percentage saturation. The percentage saturation of a machine at any excitation may be found from its saturation curve (generated voltage as ordinates, against excitation as abscissas), by drawing a tangent to the curve at the ordinate corresponding to the assigned excitation, and extending the tangent to intercept the axis of ordinates drawn through the origin. The ratio of the intercept on this axis to the ordinate at the assigned excitation, when expressed in per cent., is the percentage saturation, and is independent of the scales selected for excitation and voltage. This ratio as a fraction is equal to the reciprocal of the saturation-factor at the same excitation, deducted from unity; or, if f be the saturation-factor and p the percentage saturation,

$$p = 100\left(1 - \frac{1}{f}\right)$$

***4088. Variation in alternators.** The variation in alternators, or alternating-current circuits in general is the maximum angular displacement, expressed in electrical degrees (see Par. 3222) of corresponding ordinates of the voltage wave and of a wave of absolutely constant frequency equal to the average frequency of the alternator or circuit in question, and may be due to the variation of the prime mover. (See Pars. 14010 and 14011.)

4089. Per cent. resistance drop. The per cent. resistance drop in an electric machine is the ratio of the internal resistance drop at 75 deg. cent. to the terminal voltage expressed in per cent.

Unless otherwise specified this per cent. drop shall be referred to rated load and rated power factor.

The per cent. resistance drop in an induction motor is expressed in terms of the internally induced electromotive force.

4090. Per cent. reactance drop. The per cent. reactance drop in an electric machine or apparatus is the ratio of the internal reactance drop to the terminal voltage, expressed in per cent.

Unless otherwise specified this per cent. drop shall be referred to rated load and rated power factor.

The per cent. reactance drop in an induction motor is expressed in terms of the internally induced electromotive force.

4091. Per cent. impedance drop. The per cent. impedance drop in an electric machine is the ratio of the internal impedance drop at 75 deg. cent. to the terminal voltage, expressed in per cent.

Unless otherwise specified this per cent. drop shall be referred to rated load and rated power factor.

The per cent. impedance drop in an induction motor is expressed in terms of the internally induced electromotive force.

4092. Magnetic degree. A magnetic degree is the 360th part of the angle subtended, at the axis of a machine, by a pair of its field poles. One *mechanical degree* is thus equal to as many magnetic degrees as there are pairs of poles in the machine.

* If p is the number of pairs of poles, the variation of an alternator is p times the variation of its prime mover, if direct-connected, and pn times the variation of the prime mover if rigidly connected thereto in such a manner that the angular speed of the alternator is n times that of the prime mover.

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4094. Regulation of direct-current generators. The regulation of a rect-current generator is usually stated by giving the numerical values of e voltage at no load and rated load, and in some cases it is advisable to ate regulation at intermediate loads. The regulation of direct-current nerators refers to changes in voltage corresponding to gradual changes in ad, and does not relate to the comparatively large momentary fluctuations voltage that frequently accompany instantaneous changes in load.

4095. Regulation of constant-potential alternating-current generators. In constant-potential alternating-current generators, the regulation is the rise in voltage (when the specified load at specified power factor reduced to zero) expressed in per cent. of normal rated-load voltage.

4096. Regulation of constant-current machines. In constant-current machines the regulation is the ratio of the maximum difference of rrent from the rated-load value (occurring in the range from rated-load short-circuit, or minimum limit of operation), to the rated-load current.

4097. Regulation of constant-speed motors. In constant-speed rect-current motors and induction motors, the regulation is the ratio of e difference between full-load and no-load speeds to the no-load speed.

4098. Regulation of converters, dynamotors, motor-generators and equency converters. In converters, dynamotors, motor-generators, d frequency converters, the regulation is the change in the terminal voltage of the output side between the two specified loads. This may be expressed by giving the numerical values, or as the percentage of the terminal oltage at rated load.

OPERATION

Temperature Limits

4105. Exceptions to general temperature limits given in Chapter .

(*a*) Railway motors: See Par. **5202** and **5101**.
(*b*) Automobile propulsion machines: See Par. **5205**.
(*c*) Railway substation machines: See Par. **5201** and **5102**.
(*d*) Squirrel cage and amortisseur windings. The temperature may tain any value such as will not occasion mechanical injury to the machine.
(*e*) Field control railway motors: See Par. **5204**.

4106. Collector rings. The observable temperature of collector rings all not be permitted to exceed the values set forth in Par. **2231** (*c*) for the sulations employed either in the collector rings themselves or in adjacent sulations whose life would be affected by the heat from the collector rings.

4107. Commutators. The observable temperature shall in no case be rmitted to exceed the values given in Par. **2231** (*c*) for the insulation emoyed either in the commutator or in an insulation whose life would be fected by the heat of the commutator. These temperature limits are tended only to protect the insulation of the commutator and of the adjant parts and are not intended as a criterion of successful commutation.

4108. Cores. The observable temperature of those parts of the iron re in contact with insulating materials shall in no case be permitted to ceed the values given in Par. **2231** (*c*) for the insulation employed.

4109. Other parts (such as brush-holders, brushes, bearings, poleps, cores, etc.). All parts of electrical machinery other than those whose mperature affects the temperature of the insulating material may be opered at such temperatures as shall not be injurious in any other respect.

4110. Maximum temperature rise in service. Whatever may be the nbient temperature when the machine is in service, the limits of the maxium observable temperature or of temperature rise specified in the rules ould not be exceeded in service; for, if the maximum temperature be ceeded, the insulation may be endangered, and if the rise be exceeded, e excess load may lead to injury, by exceeding limits other than those of mperature; such as commutation, stalling load and mechanical strength. or similar reasons, loads in excess of the rating should not be taken from a achine.

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RATING

Units in Which Rating Shall be Expressed

4220. Rating of direct-current generators. The rating of direct-current generators, shall be expressed in kilowatts (kw.) available at the terminals at a specified voltage.

4221. Rating of alternators. The rating of alternators shall be expressed in kilovolt-amperes (kv-a.) available at the output terminals, at specified voltage and power factor.

***4222. Rating of motors.** It is strongly recommended that the rating of motors shall be expressed in kilowatts (kw.) available at the shaft. (An exception to this rule is made in the case of railway motors, which, for some purposes, are also rated by their *input*. See Par. **5203**.

4223. Rating of auxiliary machinery. Auxiliary machinery, such as regulators, balancer sets, synchronous-condensers, etc., shall have their ratings appropriately expressed. It is also essential to specify the voltage (and frequency, if alternating current), of the circuits on which the machinery may appropriately be used.

Limitations Other than Temperature Rise

4250. Mechanical limitations. (*a*)† *General:* All types of rotating machines shall be so constructed that they will safely withstand an overspeed of 25 per cent., except in the case of steam turbines, which, when equipped with emergency governors, shall be constructed to withstand 20 per cent. over-speed.

(*b*) *Generators:* Water-wheel generators shall be constructed for the maximum runaway speed which can be attained by the combined unit.

(*c*) *Motors:* Motors for continuous service shall, except when otherwise specified, be required to develop running torque at least 175 per cent. of that corresponding to the running torque at their rated load, without stalling. Obviously, duty-cycle machines must carry their peak loads without stalling.

4251. Commutation limitations. (*a*) *Continuously rated machines:* Continuously rated machines shall be required to commutate successfully momentary loads of 150 per cent. of the amperes corresponding to the continuous rating, keeping the rheostat set for rated load excitation. Successful commutation is such that neither brushes nor commutator are injured by the test. See Par. **2220** and **5203**.

(*b*) *Machines for duty-cycle operation:* Machines for duty-cycle operation with widely fluctuating loads, shall commutate successfully under their specified operating conditions. See Par. **2221** and **2223**.

4252. Limitations of stability. Continuously rated machines shall be required to carry momentary loads of 150 per cent. of the amperes corresponding to the continuous rating, keeping the rheostat set for rated load excitation.

In the case of direct-connected generators, this clause is not to be interpreted as requiring the prime mover to drive the generator at this overload.

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* Since the input of machinery of this class is measured in electrical units and since the output has a definite relation to the input, it is logical and desirable to measure the delivered power in the same units as are employed for the received power. Therefore, the output of motors should be expressed in kilowatts instead of in horse power. However, on account of the hitherto prevailing practice of expressing mechanical output in horse power, it is recommended that for machinery of this class the rating should, for the present, be expressed both in kilowatts and in horse power; as follows:

Kw.	Approx. equiv. h.p.

For the purposes of these rules the horsepower shall be taken as 746 watts.

In order to lay stress upon the preferred future basis, it is desirable that on rating plates, the rating in kilowatts shall be shown in larger and more prominent characters than the rating in horse power.

One kilowatt is equal to 102 kilogrammeters per second.

† In the case of series motors, it is impracticable to specify percentage values for the guaranteed overspeed, on account of the varying service conditions.

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TESTS

Ambient Temperature

4300. Measurement of the ambient temperature during tests of machines. (See Par. **2300**)(*a*) *Machines cooled by forced draught:* In the testing of rotating machines, cooled by forced draught, a conventional weighted mean shall be employed, a weight of four being given to the temperature of the circulating air supplied through ducts and a weight of one to the surrounding room air. See Par. **2300** Note.

(*b*) *Machines below floor line:* Where machines are partly below the floor line in pits, the temperature of the rotor shall be referred to a weighted mean of the pit and room temperatures, the weight of each being based on the relative proportions of the rotor in and above the pit. Parts of the stator constantly in the pit shall be referred to the ambient temperature in the pit.

Machine Temperatures

4316. Machines with small ventilating apertures. Machines having ventilating openings smaller than 0.02 sq. in. (0.13 sq. cm.) in area, when intended to be operated in locations or under conditions where the openings are liable to become clogged, should be considered as totally enclosed machines and tested as such with openings closed, and in all cases the ratings on this basis should be indicated on the rating plate.

4319. Exception to temperature limits used in method 1. In the case of enclosed motors and generators, the limits of the observable temperature rise shall be 5 deg. cent. higher than allowed by the general rule. This rule does not apply to those types of machines defined in Par. **4043**, **4045** and **4046**.

4320. Exception to temperature limits used in Method 2. In the case of enclosed motors and generators, the limits of the observable temperature rise shall be 5 deg. cent. higher than allowed by the general rule. This rule does not apply to those types of machines defined in Par. **4043**, **4045** and **4046**.

4321. Method of temperature measurement used in determining temperature of stators of machines. Method 3 should be applied to all stators of machines with cores having a width of 50 cm. (20 in.) or over. It should also be applied to all machines of 5000 volts or more, if rated over 500 kv-a., regardless of core width.

Efficiency

***4334. Classification of losses.** Losses are classified as shown in Table **401**.

†**4335. Losses to be considered in machines.** Conventional efficiencies

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* The losses in constant-potential machinery, either of the stationary type, or of the constant-speed rotary type, are of two classes; namely, those which remain substantially constant at all loads, and those which vary with the load. The former include iron losses, windage and friction, also I^2R losses in any shunt windings. The latter include I^2R losses in series windings. The constant losses may be determined by measuring the power required to operate the machine at no load, deducting any series I^2R losses. The variable loss at any load may be computed from the measured resistance of the series windings and the given load current.

† This simple method of determining the losses and hence the efficiency is only approximate, since the losses which are assumed to be constant do actually vary to some extent with the load, and also because the actual loss in the copper windings is sometimes appreciably greater than the calculated I^2R loss. The difference between the approximate losses, as above determined, and the actual losses, is termed "stray load losses." These latter are due to distortions in electric or magnetic fluxes from their no-load distributions or values, brought about by the load current. They are usually only approximately measurable, or may be indeterminable, but certain of them reach values in various kinds of machinery, which require that they should be taken into account.

Dielectric losses are usually negligible.

The stray load losses include the items in the column of Table **401** headed "Indeterminable" but do not include the increased core losses due to increased excitation for compensating internal drop under load.

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shall be based upon the losses listed in Table 402, and these losses shall be measured as specified in Par. 4336–4342 inclusive.

Table 401. Classification of losses in machinery

Accurately measurable	Approximately measurable or determinable	Indeterminable
No-load core losses including eddy-current losses in conductors at no-load	Brush friction loss	Iron loss due to flux distortion
Load I^2R losses in windings. No-load I^2R losses in windings	Brush-contact loss	Eddy-current losses in conductors due to transverse fluxes occasioned by the load currents
	Losses due to windage and to bearing friction	Eddy-current losses in conductors due to tooth saturation resulting from distortion of the main flux
		Tooth-frequency losses due to flux distortion under load
	Dielectric losses	Short-circuit loss of commutation

4336. I^2R loss. (*a*) *General:* The I^2R loss shall be based upon the current and the measured resistance.

(*b*) *Polyphase induction-motor rotor:* The I^2R loss in the rotors of polyphase induction motors should be determined from the slip, whenever the latter is accurately determinable, using the following equation:

$$\text{Rotor } I^2R \text{ loss} = \frac{\text{output} \times \text{slip}}{1 - \text{slip}}$$

Table 402. Losses in rotating electric machines

(References are to Pars.)

	I^2R loss windings	Friction and windage	Brush friction	Core loss	Brush contact I^2R loss	Stray load losses
D.-C. commutating machines (Note 1).	4336(*a*)	4337(*a*)	4338	4339	4341 5341	Note 5
A.-C. commutating machines (Note 1).	4336(*a*)	4337(*a*)	4338	4339	4341	Note 5 5339
Railway motors....	4336(*a*)	5337 5338	5338 5339	5339	4341	Note 5 5339
Synchronous motors and generators (Note 4).....	4336(*a*)	4337(*a*)	4338 Note 3	5339 4339	4341 Note 3	4342(b)
Synchronous converters.....	4336(*c*)	4337(*a*)	4338	4339(*a*) 4339(*b*)		Note 5
Induction machines	4336(*b*)	4337(*a*)	4338	4339(*a*) 4339(*c*)	4341 Note 2	4342(b)

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NOTES.—(1) Except railway motors.
(2) When there are collector rings.
(3) Brush friction and brush contact losses are negligible except in the case of revolving armature machines.
(4) For the booster type of synchronous converter, where the booster forms an integral part of the unit, its losses shall be included in the total converter losses in estimating the efficiency.
(5) These losses, while usually of low magnitude, are erratic, and the Institute is not at this time prepared to make recommendations for approximating them.

In large slip-ring motors, in which the slip cannot be directly measured by loading, the rotor I^2R loss shall be determined by direct resistance measurement; the rotor full-load current to be calculated by the following equation:

$$\text{Current per ring} = \frac{\text{watts output}}{\text{rotor voltage at stand-still} \times \sqrt{3} \times K}$$

This equation applies to three-phase rotors. For rotors wound for two phase, use 2 instead of the $\sqrt{3}$. K may be taken as 0.95 for motors of 150 h.p. or larger. The factor K usually decreases as the size of motor is reduced, but no specific value can be stated for smaller sizes.

(*c*) *Synchronous converter:* The I^2R losses in the armature winding shall be derived from those corresponding to its use as a direct-current generator, by using suitable factors.

4337. Bearing friction and windage. (*a*) *General:* Drive the machine from an independent motor, the output of which shall be suitably determined. The machine under test shall have its brushes removed and shall not be excited. This output represents the bearing friction and windage of the machine under test.

(*b*) *Induction motors:* The bearing friction and windage of induction motors may be measured by running motors free at the lowest voltage at which they will rotate continuously at approximately rated speed; the watts input, minus I^2R loss, under these conditions being taken as the friction and windage.

(*c*) *Engine-type generators:* In the case of engine-type generators, (see Par. **4027**) the windage and bearing friction loss is ordinarily very small, amounting to a fraction of one per cent. of the output. This loss shall be neglected owing to its small value and the difficulty of measuring it.

(*d*) *Direct-current railway motors:* See Par. **5337.**

4338. Brush friction of commutator and collector rings. (*a*) *General:* Drive the machine from an independent motor, the output of which shall be suitably determined. The brushes shall be in contact with the commutator or collector rings, but the machine shall not be excited. The difference between the output obtained in the test in Par. **4337** and this output shall be taken as the brush friction. The surfaces of the commutator and brushes should be smooth and glazed from running when this test is made.

(*b*) *Direct-current railway motors:* See Par. **5338.**

4339. Core losses. (*a*) *General:* Drive the machine from an independent motor, the output of which shall be suitably determined. The brushes shall be in contact, and the machine shall be excited, so as to produce at the terminals a voltage corresponding to the calculated internal voltage for the load under consideration. The difference between the output obtained by this test and that obtained by test under Par. **4338** (*a*) shall be taken as the core loss.

(*b*) *Synchronous machines:* The internal voltage of synchronous machines shall be determined by correcting the terminal voltage for the resistance drop only.

(*c*) *Induction motors:* The core loss of an induction motor may be determined by measuring the watts input to the motor when running free at rated voltage and frequency and subtracting therefrom the no-load copper loss, bearing friction and windage.

(*d*) *Direct-current railway motors:* See Par. **5339.**

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*4341. **Brush-contact I^2R loss.** (*a*) *General:* One volt drop per brush shall be considered as the Institute standard drop corresponding to the I^2R brush-contact loss, for carbon and graphite brushes with pigtails attached. One and one-half volts per brush shall be allowed where pigtails are not attached. Metal-graphite brushes shall be considered as special.

(*b*) *Automobile motors:* See Par. 5341.

†4342. **Stray load-losses.** (*a*) *Synchronous machines:* These include iron losses, and eddy-current losses in the copper, due to fluxes varying with load and also to saturation.

Stray load-losses shall be determined by operating the machine on short circuit and at rated-load current. This, after deducting the windage and friction and I^2R loss, gives the stray load-loss for polyphase generators and motors. These losses in single-phase machines are large; but the Institute is not yet prepared to specify a method for measuring them.

(*b*) *Induction machines:* These include eddy-current losses in the stator copper, and other eddy-current losses due to fluxes varying with the load. In windings consisting of relatively small conductors, these eddy-current losses are usually negligible.

With rotor removed, measure the power input to the stator with different values of current at the rated frequency. The curve plotted with these values gives the combined I^2R and stray load-losses due to eddy-currents in the stator copper. Deduct the I^2R loss determined from the resistance, and the difference will represent the stray load-losses corresponding to the various currents. While this method is not accurate for some types of motors it usually represents a sufficiently good approximation.

4343. **Miscellaneous losses.** (*a*) *Field-rheostat losses:* Field-rheostat losses shall be included in the generator losses where there is a field rheostat in series with the field magnets of the generator, even when the machine is separately excited.

(*b*) *Ventilating blower:* When a blower is supplied as part of a machine set, the power required to drive it shall be charged against the complete unit, but not against the machine alone.

(*c*) *Other auxiliary apparatus:* Auxiliary apparatus, such as a separate exciter for a generator or motor, shall have its losses charged against the plant of which the generator and exciter are a part, and not against the generator. An exception should be noted in the case of turbo-generator sets with direct-connected exciters, in which case the losses in the exciter shall be charged against the generator. The actual energy of excitation and the field-rheostat losses, if any shall be charged against the generator. See Par. 4343 (*a*).

Wave Shape

4351. **Deviation factor of a wave.** The deviation factor of the open circuit terminal voltage wave of synchronous machines shall not exceed 10 per cent. unless otherwise specified. See Par. 2374.

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* The brush-contact I^2R loss depends largely upon the material of which the brush is composed.

As indicating the range of variation the following table will be of interest:

Table 403. Brush-contact drop

Grade of brush	Volts drop across one brush-contact (Average of positive and negative brushes)
Hard carbon	1.1
Soft carbon	0.9
Graphite	0.5 to 0.8
Metal-graphite types	0.15 to 0.5 (The former for largest proportion of metal)

† Values of the indeterminable losses may also be obtained by brake or other direct test and used in estimating actual efficiencies of similar machines by the separate-loss method.

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4352. Telephone interference factor of a wave. (For trial only.) (See Par. 2278.) (a) *Conditions of test.* The weighting of the sine wave components of different frequencies shall be as given in Fig. 4-1.

The telephone interference factor of a voltage wave, corresponding to this weighting, may be measured by the use of the network shown in Fig. 4-2.

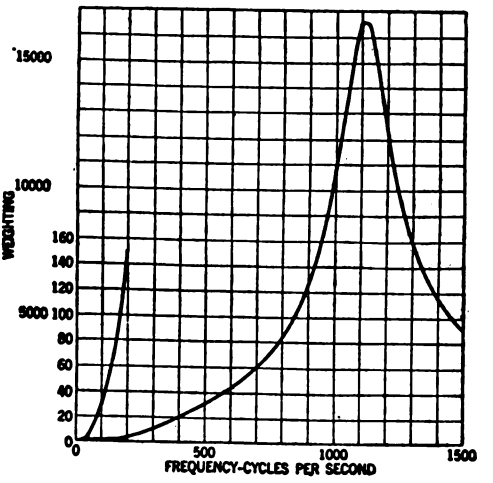
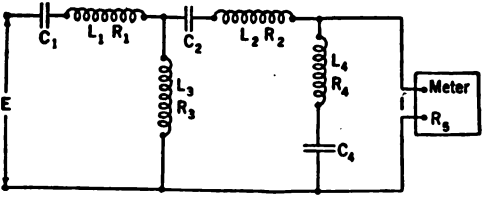


FIG. 4-1



Network Constants

$C_1 = 0.9$ mf.			$L_1 = 0.023$ henry		$R_1 = 5$ ohms ±2%
$C_2 = 0.9$ "			$L_2 = 0.0205$ "		$R_2 = 12$ " ±2%
	±0.5%		$L_3 = 0.068$ "	±0.5%	$R_3 = 73$ " ±1%
$C_4 = 7.5$ "			$L_4 = 0.019$ "		$R_4 = 22.5$ " ±2%
					$R_5 = 43$ " ±1%

FIG. 4-2

With this network the telephone interference factor of a voltage wave is the ratio of the current I in micro-amperes in the meter branch of the network to the voltage E applied to the external terminals of the network. The measurement may be made on the low tension side of a potential transformer. A sensitive vacuum thermocouple provided with a shunt, and a direct-current mil-ammeter have been found convenient for measuring the current.

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(b) The appropriate limiting value of the telephone interference factor a wave (see Par. 3378), either for machines or for circuits, has not yet been determined, and cannot now be specified. The whole matter of interference, including reasonable requirements for both power and communication systems, is under discussion, in consultation with power, telephone, and other interests concerned.

Tests of Dielectric Strength

4358. Frequency of test voltage. In direct-current machines, and in general commercial application of alternating machines, the testing frequency of 60 cycles per second is recommended.

***4361. Exceptions to standard test voltage given in section 2361.**

(a) *Field windings of alternating-current generators:* Field windings of alternating-current generators shall be tested with 10 times the exciter voltage but in no case with less than 1,500 volts nor more than 3,500 volts.

*(b) *Field windings of synchronous machines:* Field windings of synchronous machines including motors and converters which are to be started with alternating current are to be tested as follows:

When machines are to be started with field short circuited, the field windings shall be tested as specified in Par. 4361 (a).

When machines are to be started with fields open circuited and sectionalized while starting, the field windings shall be tested with 5,000 volts.

When machines are to be started with fields open circuited and connected all in series while starting, the windings shall be tested with 5,000 volts for less than 275 volts excitation and 8,000 volts for excitation of 275 volts to 275 volts.

†(c) *Phase-wound rotors of induction motor:* The secondary windings of wound rotors of induction motors shall be tested with twice their normal induced voltage, plus 1,000 volts. When induction motors with phase-wound rotors are to be reversed, while running at approximately normal speed, by reversing the primary connections, the test shall be four times the normal induced voltage plus 1,000 volts.

(d) *Small motors and generators:* Small machines taking not over 660 watts or having an output not exceeding ½ h.p. (373 watts), such as fractional horsepower motors, and intended solely for operation on supply circuits not exceeding 275 volts, shall be tested with 900 volts.

(e) *Alternating-current machines connected to permanently grounded single-phase systems:* Alternating-current machines connected to permanently grounded single-phase systems, for use on permanently grounded circuits operating at more than 300 volts shall be tested with 2.73 times the voltage of the circuit to ground, plus 1,000 volts. This does not refer to three-phase machines with grounded star neutral.

‡(f) *Machines for use on circuits of 25 volts or lower:* Machines for use on circuits of 25 volts or lower, such as bell ringing apparatus, electric machines used in automobiles, machines used on low voltage battery circuits, etc., shall be tested with 500 volts.

Regulation

4390. Conditions for tests of regulation (see Par. 2390). (a) *Power factor:* In alternating-current generators the power factor of the load to which the regulation refers should be specified. Unless otherwise specified, it shall be understood as referring to non-inductive load, that is, to a load in which the current is in phase with the e.m.f. at the terminals of the machine.

(b) *Excitation:* In commutating machines, rectifying machines and synchronous machines, the regulation shall be determined under such conditions as to maintain the field adjustment constant at a value which gives rated-load voltage at rated-load current. These conditions are as follows:

In the case of separately excited fields: constant excitation.

In the case of shunt machines: constant resistance in the shunt-field circuit.

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* Series-field windings should be regarded as part of the armature circuit and tested as such.

† By normal induced voltage is here meant the voltage between slip rings on open circuit at standstill with normal voltage impressed on the primary.

‡ The present National Electrical Code limit for a single outlet is 660 watts.

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In the case of series or compound machines: constant resistance shunting ie series field windings.

***4394. Tests and computation of regulation of alternating-current ;nerators.** (*a*) *Methods available:* The regulation of alternating-current :nerators may be determined by any one of the three following methods, hich are given in the order of preference:

(*b*) *Method I. By loading:* The regulation can be measured directly, by ading the generator at the specified output and power factor, then reducing ie load to zero, and measuring the terminal voltage, with speed and ex- tation adjusted to the same values as before the change. This method is ot generally applicable for shop tests, particularly on large generators and becomes necessary to determine the regulation from such other tests as an be readily made.

*(*c*) *Method II. From test curves:* This method consists in computing ie regulation from experimental data of the open-circuit saturation curves nd the zero-power-factor saturation curve. The latter curve, or one pproximating very closely to it, can be obtained by over-exciting the gen- rator while carrying a load of idle-running under-excited synchronous iotors. The power factor under these conditions is very low and the load ituration curve approximates very closely the zero power-factor saturation urve. From this curve and the open circuit curve, points for the load ituration curve for any specified power factor can be obtained by means of ector diagrams.

* Method II for deducing the load saturation curve, at any assigned power ictor, from no-load and zero power-factor saturation curves obtained by test, iust be regarded as empirical. Its value depends upon the fact that ex- erience has demonstrated the reasonable correctness of the results obtained y it.

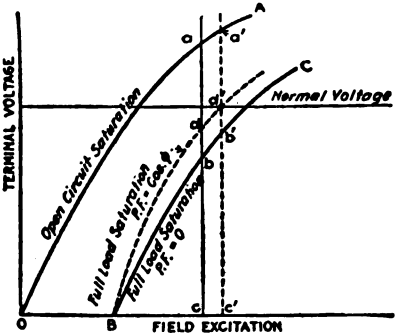


FIG. 4-3

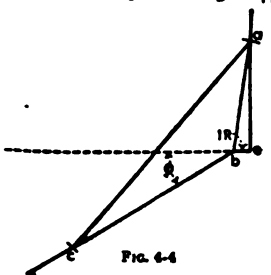


FIG. 4-4

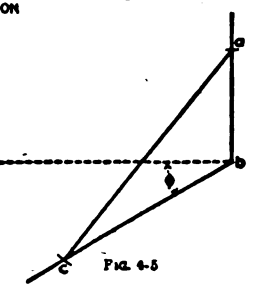


FIG. 4-5

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†(d) *Method III. From estimated zero power-factor curve.* Where it is not possible to obtain by test a zero power-factor curve as in Method II this curve can be estimated closely from open-circuit and short-circuit curves by reference to tests at zero power-factor on other machines of similar magnetic circuit. Having obtained the estimated zero power-factor curve, the load saturation for any other power factor is obtained as in Method II. Par. 4394(c).

To apply method II, it is necessary to obtain from test the open-circuit saturation curve, Fig. 4-3, and the load saturation curve *BC* at zero power-factor and rated-load current. At any given excitation *Oc*, the voltage that would be induced on open circuit is *ca*, the terminal voltage at zero power-factor is *cb* and the apparent internal drop is *ab*. The terminal voltage at

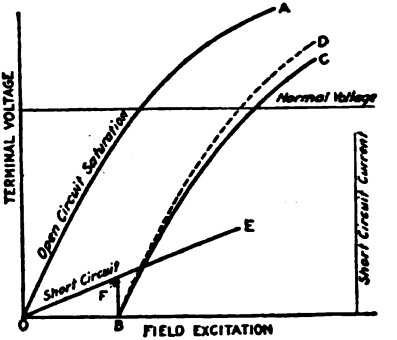


FIG. 4-6

at any other power factor can then be found by drawing an e.m.f. diagram as in Fig. 4-4, where ϕ is an angle such that $\cos\phi$ is the power factor of the load, *be* the resistance drop (*IR*) in the stator winding, *ba* the total internal drop and *ac* the total induced voltage; *ba* and *ac* being laid off to correspond with the values obtained from Fig. 4-3. The terminal voltage at power-factor $\cos\phi$ is then *cb*, Fig. 4-4, which when laid off in Fig. 4-3 gives point *d*. By finding a number of such points, the curve *Bdd'* for power factor $\cos\phi$ is obtained and the regulation at this power factor (expressed in per cent) is $\frac{100 \times a'd'}{c'd'}$ since *a'd'* is the rise in voltage when the load at power factor $\cos\phi$ is thrown off at normal voltage *c'd'*.

† Method III is the same as Method II except that the zero power-factor curve must be estimated. This may be done as follows. In Fig. 4-6, *OA* is the open-circuit saturation curve and *OB* the short-circuit line as obtained from test. The zero power-factor curve corresponding to any current *BF* will start from point *B*, and for machines designed with low saturation and low reactance, will follow parallel to *OA* as shown by the dotted curve *BE*, which is *OA* shifted horizontally parallel to itself by the distance *OB*. In high-speed machines, or in others having low reactance, and a low degree of saturation in the magnetic circuit, the zero power-factor curve will be quite close to *BD* particularly in those parts that are used for determining the regulation. This is the case with many turbo-generators and high-speed water-wheel generators.

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Generally, the ohmic drop can be neglected as it has little influence on he regulation, except in very low-speed machines where the armature drop relatively high or in some cases where regulation at unity power factor is eing estimated. For low power factors its effect is negligible in practically ll cases. If resistance is neglected, the simpler diagram, Fig. 4-5, may be sed.

In many cases, however, the zero power-factor curve will deviate from *D*, as shown by *BC* and the deviation will be most pronounced in machines high reactance, high saturation and large magnetic leakage. The position curve *BC* with relation to *BD* can be approximated with sufficient exact- ss by investigating the corresponding relation as obtained by test at zero ower factor on machines of similar characteristics and magnetic circuit. urve *BC* can also be calculated by methods based on the results of tests zero power-factor. After curve *BC* has been obtained, the load satura- on curve and regulation for any other power factor can be derived as in ethod II, Par. 4394(*c*).

4395. Compound wound direct-current generator. In determining e regulation of a compound-wound direct-current generator, two tests all be made, one bringing the load down and the other bringing the load , between no-load and rated load. These may differ somewhat, owing to idual magnetism. The mean of the two results shall be used.

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CHAPTER V

STANDARDS FOR ELECTRIC RAILWAYS AND FOR AUTOMOBILE PROPULSION MACHINES

he A. I. E. E. standards for electric railways and for automobile propul- machines are the general standards shown in Chapters II and III, and standards in other chapters which are applicable to the devices involved ther with the modifications and extensions given in this chapter.

DEFINITIONS

General

000. Contact conductors. A contact conductor is that part of the ibution system other than the traffic rails, which is in immediate elec- l contact with the circuits of the cars or locomotives.

Contact Rails

003. Contact rail. (*a*) *General:* A contact rail is a rigid contact uctor.

(*b*) *Overhead contact rail:* An overhead contact rail is a contact rail which ove the elevation of the maximum equipment line.

The maximum equipment line is the contour which embraces cross-sec- of all rolling stock under all normal operating conditions.

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(c) *Third rail:* A third rail is a contact conductor placed at either side of the track, the contact surface of which is a few inches above the level of the top of the track rails.

(d) *Center contact rail:* A center contact rail is a contact conductor placed between the track rails, having its contact surface above the ground level.

(e) *Underground contact rail:* An underground contact rail is a contact conductor placed beneath the ground level.

(f) *Gage of third rail:* The gage of a third rail is the distance, measured parallel to the plane of running rails, between the gage line of the nearer track rail and the inside gage line of the contact surface of the third rail.

(g) *Elevation of third rail:* The elevation of a third rail is the elevation of the contact-surface of the third rail, with respect to the plane of the tops of running rails.

(h) *Third rail protection:* A third rail protection is a guard for the purpose of preventing accidental contact with the third rail.

Trolley Wires

5004. Trolley wire. A trolley wire is a flexible contact conductor customarily supported above the cars.

5005. Messenger wire or cable. A messenger wire or cable is a wire or cable running along with and supporting other wires, cables or contact conductors.

A primary messenger is directly attached to the supporting system. A secondary messenger is intermediate between a primary messenger and the wires, cables or contact conductors.

5006. Classes of construction. (a) *General:* Overhead trolley constructions are classed as *direct suspension* and *messenger or catenary suspension.*

(b) *Direct suspension:* A direct suspension is the form of overhead trolley construction in which the trolley wires are attached, by insulating devices, directly to the main supporting system.

(c) *Messenger or catenary suspension:* A messenger or catenary suspension is the form of overhead trolley construction in which the trolley wires are attached, by suitable devices, to one or more messenger cables, which in turn may be carried either in *simple catenary*, i.e., by primary messengers, or in *compound catenary*, i.e., by secondary messengers.

5007. Supporting systems. (a) *General:* Supporting systems for trolley wires shall be classed as follows:

(b) *Simple cross-span systems:* Simple cross-span systems are those having at each support a single flexible span across the track or tracks.

(c) *Messenger cross-span systems:* Messenger cross-span systems are those having at each support two or more flexible spans across the track or tracks, the upper span carrying part or all of the vertical load of the lower span.

(d) *Bracket systems:* Bracket systems are those having at each support an arm or similar rigid member, supported at only one side of the track or tracks.

(e) *Bridge systems:* Bridge systems are those having at each support a rigid member, supported at both sides of the track or tracks.

*5030. **Transmission system.** When the current generated for an electric railway is changed in kind or voltage, between the generator and the cars or locomotives, that portion of the conductor system carrying current of a kind or voltage substantially different from that received by the cars or locomotives, constitutes the *transmission system.*

*5031. **Distribution system.** That portion of the conductor system of an electric railway which carries current of the kind and voltage received by the cars or locomotives, constitutes the *distribution system.*

5032. **Substation.** A substation is a group of apparatus or machinery which receives current from a transmission system, changes its kind or voltage, and delivers it to a distribution system.

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* These definitions are identical in sense, although not in words, with those of the Interstate Commerce Commission, as given in their Classification of Accounts for Electric Railways.

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OPERATION

Temperature Limits

***5101. Railway motors in continuous service.** The following maximum observable temperatures are permissible in the windings of railway motors, when in continuous service.

Table 501. Temperatures of railway motors in continuous service

Class of material (see Par. 1004)	Temperature	
	By thermometer (see Par. 1002)	By resistance (see Par. 1002)
A.....	85 deg. cent.	110 deg. cent.
B.....	100 deg. cent.	130 deg. cent.

5120. Railway substation machines and transformers. Under conditions specified in Par. 5201, the windings of railway substation machines and transformers carrying traction loads may have observable temperatures 5 deg. cent. in excess of the limiting observable temperature rises specified in Table 200.

***5130. Automobile propulsion machines.** On stand test, the observable temperature rises shall not exceed the limits specified in Par. 5205.

RATING

Ratings of Railway Substation Machinery and Transformers

†5201. Nominal rating of railway substation machines and transformers. The nominal rating of a substation machine or transformer carrying traction loads shall be the kv-a. output at a stated power-factor input, which, having produced a constant temperature in the machine or transformer may be increased 50 per cent. for two hours, without producing temperature rises exceeding by more than 5 deg. cent. the limiting values given in Table 200. These machines or transformers should be capable of carrying a load of twice their nominal rating for a period of one minute, without disqualifying them for continuous service. The name plate should be marked "nominal rating."

Ratings of Railway Motors

†5202. Nominal rating of railway motors. The nominal rating of a railway motor shall be the mechanical output at the car or locomotive axle, measured in kilowatts, which causes a rise of temperature above the surrounding air, by thermometer, not exceeding 90 deg. cent. at the commutator, and 75 deg. cent. at any other normally accessible part after one hour's continuous run at its rated voltage (and frequency in the case of an alternating-current motor) on a stand with the motor covers arranged to secure maximum ventilation without external blower. The rise in temperature measured by resistance, shall not exceed 100 deg. cent. The statement of the nominal rating shall include the corresponding voltage and armature speed.

§5203. Continuous ratings of railway motors. The continuous rat-

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* Under extreme ambient temperatures it is permissible to operate, for short infrequent periods, at 15 deg. cent. higher temperature than specified in this rule.

Owing to space limitations and the cost of carrying dead weight on vehicles, it is considered good practise to operate propulsion machinery at higher temperatures than would be advisable in stationary machines. (See Table 501.)

† In the absence of any specification as to the kind of rating the "nominal" rating shall be understood.

§ The temperature rise in service may be very different from that on stand-test. See Par. 5502 for the relation between stand-test and service temperatures as affected by ventilation.

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ings of a railway motor shall be the *inputs* in amperes at which it may be operated continuously at ½, ¾ and full voltage respectively, without exceeding the observable temperature rises specified in Table 502, when operated on stand test with motor covers and cooling system, if any, arranged as in service. Inasmuch as the same motor may be operated under different conditions as regards ventilation, it will be necessary in each case to define the system of ventilation which is used. In case motors are cooled by external blowers, the flow of air on which the rating is based shall be given.

Table 502. Stand-test temperature rises of railway motors

Class of material (see Par. 1004)	Temperature rises of windings	
	By thermometer (see Par. 1002)	By resistance (see Par. 1002)
A	65 deg. cent.	85 deg. cent.
B	80 deg. cent.	105 deg. cent.

5204. Field-control railway motors. The nominal and continuous ratings of field-control motors shall relate to their performance with the operating field which gives the maximum motor rating. Each section of the field windings shall be adequate to perform the service required of it without exceeding the specified temperature rises.

Ratings of Automobile Propulsion Machines

5205. Automobile propulsion machines. The rating of automobile motors and generators shall be based upon temperature rise, on a stand test and with motor covers arranged as in service, fifteen degrees by thermometer or twenty five degrees by resistance, above those of Table 502.

Ratings of Electric Locomotives

5210. Rating. Locomotives shall be rated in terms of the weight on drivers, nominal one-hour tractive effort, continuous tractive effort and corresponding speeds.

5211. Weight on drivers. The weight on drivers, expressed in pounds, shall be the sum of the weights carried by the drivers and of the drivers themselves.

5212. Nominal tractive effort. The nominal tractive effort, expressed in pounds, shall be that exerted at the rims of the drivers when the motors are operating at their nominal (one-hour) rating.

5213. Continuous tractive effort. The continuous tractive effort, expressed in pounds, shall be that exerted at the rims of the drivers when the motors are operating at their full-voltage continuous rating, as indicated in Par. 5203.

In the case of locomotives operating on intermittent service, the continuous tractive effort may be given for ½ or ¾ voltage, but in such cases the voltage shall be clearly specified.

5214. Speed. The rated speed, expressed in miles per hour, shall be that at which the continuous tractive effort is exerted.

TESTS

Efficiency

Losses in Direct-current Railway Motors

5227. Losses in gearing and axle bearings. The losses in gearing and axle bearings for single-reduction single-geared motors, varies with the type, mechanical finish, age and lubrication. The following values, based upon accumulated tests, shall be used in the comparison of single-reduction single-geared motors, Par. 5229.

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ıble 503. Losses in axle bearings and single-reduction gearing of railway motors

?er cent. of input at nominal rating	Losses as per cent. of input	Per cent. of input at nominal rating	Losses as per cent. of input
200	3.5	60	2.7
150	3.0	50	3.2
125	2.7	40	4.4
100	2.5	30	6.7
75	2.5	25	8.5

NOTE.—Further investigation may indicate the desirability of givin parate values of the losses for full and tapped fields, or low- and high-speed otors.

5338. Brush friction, armature-bearing friction and windage. The ush friction, armature-bearing friction and windage, shall be determined a total under the following conditions:

In making the test, the motor shall be run without gears. The kind of ushes and the brush pressure shall be the same as in commercial service. rive the machine idle as a series motor on low voltage. The product of mature counter-electromotive-force and amperes at any speed shall be e sum of the above losses at that speed. See Par. **5339.**

***5339. No-load core loss, brush friction, armature-bearing friction ıd windage.** The no-load core loss, brush friction, armature-bearing ıction and windage shall be determined as a total under the following ınditions:

In making the test, the motor shall be run without gears. The kind of ushes and the brush pressure shall be the same as in commercial service. ith the field separately excited, such a voltage shall be applied to the mature terminals as will give the same speed for any given field current is obtained with that field current when operating at normal voltage under ad. The sum of the losses above-mentioned, is equal to the product of e counter-electromotive force and the armature current.

The no-load core loss is obtained by deducting from the total losses thus otained the power required to drive the motor at corresponding speeds as termined under Par. **5338.**

The core loss under load shall be assumed to have the values given in able **504.**

able 504. Core loss in direct-current railway motors at various loads

Per cent. of input at nominal rating	Loss as per cent. of no-load core loss	Per cent. of input at nominal rating	Loss as per cent. of no-load core loss
200	165	75	125
150	145	50	123
100	130	25 and under	122

NOTE.—With motors designed for field control the core losses shall be ıumed as the same for both full and permanent field. It shall be the ean between the no-load losses at full and permanent field, increased by e percentages given in the above Table.

5341. Automobile motors. When automobile motors are of low volt- ge, the great influence of brush-contact losses on the efficiency requires at these losses be determined experimentally for the type of brush used.

*In comparing projected railway motors, and in case it is not possible or esirable to make tests to determine mechanical losses, the following values f these losses, see table **505,** determined from the averages of many tests ver a wide range of sizes of single-reduction single-geared motors, will be ound useful, as approximations. They include axle-bearing, gear, armature- earing, brush-friction, windage, and stray-load losses.

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Table 505. Approximate losses in direct-current railway motors

Input in per cent. of that at nominal rating	Losses as per cent. of input	Input in per cent. of that at nominal rating	Losses as per cent. of input
100 or over	5.0	40	8.8
75	5.0	30	13.3
60	5.3	25	17.0
50	6.5		

The core loss of railway motors may also be determined as specified for ther machines.

CHARACTERISTIC CURVES OF RAILWAY MOTORS

5401. General. The characteristic curves of railway motors shall be lotted with the current as abscissas and the tractive effort, speed and efficiency as ordinates. In the case of alternating-current motors, the power actor shall also be plotted as ordinates.

5402. Voltage. Characteristic curves of direct-current motors shall be ased upon full voltage, which shall be taken as 600 volts, or a multiple hereof.

5403. Field-control motors. In the case of field-control motors, characteristic curves shall be given for all operating field connections.

SELECTION OF RAILWAY MOTOR FOR SPECIFIED SERVICE

5501. Data required in selecting motor. The following information elative to the service to be performed, is required, in order that an appro- riate motor may be selected.

(*a*) Weight of total number of cars in train (in tons of 2,000 lb.) exclusive f electrical equipment and load.

(*b*) Average weight of load and durations of same, and maximum weight f load and durations of same.

(*c*) Number of motor cars or locomotives in train, and number of trailer ars in train.

(*d*) Diameter of driving wheels.

(*e*) Weight on driving wheels, exclusive of electrical equipment.

(*f*) Number of motors per motor car.

(*g*) Voltage at train with power on the motors—average, maximum and ainimum.

(*h*) Rate of acceleration in miles per hour per second.

(*i*) Rate of braking (in miles per hour per second).

(*j*) Speed limitations, if any (including slowdowns).

(*k*) Distances between stopping points.

(*l*) Average duration of stops.

(*m*) Schedule speed, including stops, in miles per hour.

(*n*) Train resistance in pounds per ton of 2,000 lb. at stated speeds.

(*o*) Moment of inertia of revolving parts, exclusive of electrical equipnent.

(*p*) Profile and alignment of track.

(*q*) Distance coasted as a percentage of the distance between stoping oints.

(*r*) Duration of layover at end of run, if any.

***5502. Method of comparing motor capacity with service requirements.** When it is not convenient to test motors under actual service conditions, recourse ma mining temperature rise from t

The essential motor losses a the motor windings, core and may be expressed, as a close current and core loss which wi of losses as the average in servi

A stand test with the curren those in service, will determin to meet the service requireme enclosed motor (Par. 4044), we moving car or locomotive, will the character of the service) of t with the motor completely en ventilated motor (Par. 4045 an will be 90 to 100 per cent. of t with the same losses.

In making a stand test to d service, it is essential in the ca according to curves which can b cedure is therefore as follows:

(*a*) Plot a time-current curve curve for the duty-cycle which these the root-mean-square curr

(*b*) If the calculated r.m.s. se when run with average service c powerful for the duty-cycle con

(*c*) If the calculated r.m.s. ser rating, when run with average s narily suitable for the service.

In some cases, however, it m avoid excessive temperature rise cases a further calculation is re the equivalent voltage which, wi age core loss. Having obtained rise due to the r.m.s. service cur

Let t = temperature rise
p_c = I^2R loss, kw.
p_e = core loss, kw.
T = temperature rise
P_c = I^2R loss, kw.
P_e = core loss, kw.

Then

$$t = T\frac{p_c}{P_c}$$

(*d*) The thermal capacity of ratio of the electrical loss in kilo the corresponding maximum ob test starting at ambient temper

(*e*) Consider any period of p in kilowatt-hours during that Find the excess of the above loss and equivalent voltage. The e mal capacity, will equal the ex This temperature rise added to equivalent voltage, gives the to ture rise in any such period exce powerful for the service.

(*f*) If the temperature reache safe limit, the motor may yet be may cause excessive sparking therefore, necessary to compare load capacity. If the peaks a may be considered suitable for

* Calculation for comparing motor capacity with service requirements. The heating of a motor should be determined, wherever possible, by testing t in service, or with an equivalent duty-cycle. When the service or equivalent duty-cycle tests are not practicable, the ratings of the motor may be utilized as follows to determine its temperature rise.

The motor losses which affect the heating of the windings are as stated above, those in the windings and in the core. The former are proportional to the square of the current. The latter vary with the voltage and current,

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rvice conditions, recourse may be had to the following method of deter-
ining temperature rise from the stand-tests.
The essential motor losses affecting temperatures in service are those in
e motor windings, core and commutator. The mean service conditions
ay be expressed, as a close approximation, in terms of that continuous
rrent and core loss which will produce the same losses and distribution
losses as the average in service.
A stand test with the current and voltage which will give losses equal to
ose in service, will determine whether the motor has sufficient capacity
meet the service requirements. In service, the temperature rise of an
closed motor (Par. **4044**), well exposed to the draught of air incident to a
oving car or locomotive, will be from 75 to 90 per cent. (depending upon
e character of the service) of the temperature rise obtained on a stand test
th the motor completely enclosed and with the same losses. With a
ntilated motor (Par. **4045** and Par. **4046**), the temperature rise in service
ll be 90 to 100 per cent. of the temperature rise obtained on a stand test
th the same losses.
In making a stand test to determine the temperature rise in a specific
rvice, it is essential in the case of a self-ventilated motor (Par. **4046**) to

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cording to curves which can be supplied by the manufacturers. The pro-
dure is therefore as follows:
(*a*) Plot a time-current curve, a time-voltage curve, and a time-core loss
rve for the duty-cycle which the motor is to perform, and calculate from
se the root-mean-square current and the average core loss.
(*b*) If the calculated r.m.s. service current exceeds the continuous rating,
en run with average service core loss and speed, the motor is not sufficiently
werful for the duty-cycle contemplated.
(*c*) If the calculated r.m.s. service current does not exceed the continuous
ing, when run with average service core loss and speed, the motor is ordi-
rily suitable for the service.
In some cases, however, it may not have sufficient thermal capacity to
oid excessive temperature rises during the periods of heavy load. In such
es a further calculation is required, the first step of which is to compute
equivalent voltage which, with the r.m.s. current, will produce the aver-
core loss. Having obtained this, determine, as follows, the temperature
due to the r.m.s. service current and equivalent voltage.

t = temperature rise
$p_0 = I^2R$ loss, kw.
p_e = core loss, kw.

} with r.m.s. service current, and equivalent service voltage.

T = temperature rise
$P_0 = I^2R$ loss, kw.
P_e = core loss, kw.

} with continuous load current corresponding to the equivalent service voltage.

en

$$t = T\frac{p_0 + p_e}{P_0 + P_e}, \text{ approximately.}$$

d) The thermal capacity of a motor is approximately measured by the
io of the electrical loss in kilowatts at its nominal (one-hour) capacity, to
corresponding maximum observable temperature rise during a one-hour
starting at ambient temperature.
e) Consider any period of peak load and determine the electrical losses
kilowatt-hours during that period from the *electrical* efficiency curve.
d the excess of the above losses over the losses with r.m.s. service current
equivalent voltage. The excess loss, divided by the coefficient of ther-
capacity, will equal the extra temperature rise due to the peak load.
is temperature rise added to that due to the r.m.s. service current, and
uivalent voltage, gives the total temperature rise. If the total tempera-
e rise in any such period exceeds the safe limit, the motor is not sufficiently
werful for the service.
f) If the temperature reached, due to the peak loads, does not exceed the
limit, the motor may yet be unsuitable for the service, as the peak loads
y cause excessive sparking and dangerous mechanical stresses It is,
refore, necessary to compare the peak loads with the short-period over-
d capacity. If the peaks are also within the capacity of the motor, it
y be considered suitable for the given duty-cycle.

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run the armature at a speed which corresponds to the schedule speed in service. In order to obtain this speed it may be necessary, while maintaining the same total armature losses, to change somewhat the ratio between the I^2R and core-loss components.

CONSTRUCTION

***5601. Standard height of trolley wire on street and interurban railways.** It is recommended that supporting structures shall be of such height that the lowest point of the trolley wire shall be at a height of 18 ft. (5.5 m.) above the top of rail under conditions of maximum sag, unless local conditions prevent. On trackage operating electric and steam road equipment and at crossings over steam roads, it is recommended that the trolley wire shall be not less than 21 ft. (6.4 m.) above the top of rail, under conditions of maximum sag.

5602. Standard gage of third rails. The gage of third rails shall be not less than 26 in. (66 cm.) and not more than 27 in. (68.6 cm.).

5603. Standard elevation of third rails. The elevation of third rails shall not be less than 2¾ in. (7 cm.) and not more than 3½ in. (8.9 cm.).

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CHAPTER VI

STANDARDS FOR TRANSFORMERS AND OTHER STATIONARY INDUCTION APPARATUS

Wherever the general standards in Chapters II and III apply to transformers they are referred to in the following chapter by cross references.

Certain rules applying exclusively to railway machinery have, for convenience, been placed in Chapter V with cross reference in all cases to this chapter. Rules in Chapter VI apply to railway machinery except as they are modified by the rules in Chapter V.

NOTE.—The word "Transformer" will be used throughout this chapter as an abbreviation of "Transformer or other stationary induction apparatus."

DEFINITIONS

Apparatus

6000. Stationary induction apparatus. For the purpose of these standards stationary induction apparatus is defined as electric apparatus which changes electric energy to electric energy through the medium of magnetic energy, without mechanical motion. It comprises several forms as defined in Pars. **6001** and **6010** to **6015**.

6001. Transformer. A transformer is a form of stationary induction apparatus in which the primary and secondary windings are ordinarily insulated one from another.

6010. Auto-transformer. An auto-transformer is one which has a part of its turns common to both primary and secondary circuits.

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* A. E. R. A. Standard.

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6011. Voltage-regulator. A voltage-regulator is a form of stationary luction apparatus which has turns in shunt and turns in series with the cuit, so arranged that the voltage ratio of the transformation, or the phase ation between the circuit-voltages, is variable at will.

6012. Contact voltage regulator. A contact voltage regulator is a ltage regulator in which the number of turns in one or both of the coils is justable.

6013. Induction voltage regulator. An induction voltage regulator one in which the relative position of the primary and secondary coils is justable.

6014. Magneto voltage regulator. A magneto voltage regulator is one in iich the direction of the magnetic flux with respect to the coils is adjustable.

6015. Reactor. A reactor is a device used primarily because it possesses e property of reactance. Reactors are used in electric circuits for purses of operation, protection or control.

Parts of Apparatus

6020. High-voltage and low-voltage winding. The terms "high ltage" and "low voltage" are used to distinguish the winding having the eater from that having the lesser number of turns.

6021. Primary and secondary windings. The term "primary" and econdary" serve to distinguish the windings in regard to energy flow, the imary being that which receives the energy from the supply circuit, and e secondary that which receives the energy by induction from the primary.

Properties of Apparatus

6031. Rated current of a constant-potential transformer. The ted current of a constant-potential transformer is that secondary current iich, multiplied by the rated-load secondary voltage, gives the kilovoltmpere rated output. That is, a transformer of given kilovolt-ampere ting must be capable of deliveripg the rated output at rated secondary ltage, while the primary impressed voltage is increased to whatever value necessary to give rated secondary voltage.

6032. Rated primary voltage of a constant-potential transformer. ie rated primary voltage of a constant-potential transformer is the rated condary voltage multiplied by the turn ratio.

6033. Ratio of a transformer. The ratio of a transformer, unless otherse specified, shall be the ratio of the number of turns in the high-voltage nding to that in the low-voltage winding; i.e., the "turn-ratio."

6034. Voltage ratio of a transformer. The voltage ratio of a transrmer is the ratio of the r.m.s. primary terminal voltage to the r.m.s. secidary terminal voltage, under specified conditions of load.

6035. Current ratio of a transformer. The current ratio of a currentansformer is the ratio of the r.m.s. primary current to the r.m.s. secondary rrent, under specified conditions of load.

6036. Volt-ampere ratio of transformer. The volt-ampere ratio, hich should not be confused with real efficiency, is the ratio of the voltmpere output to the volt-ampere input of a transformer, at any given wer factor.

***6050. Per cent. resistance drop.** The per cent. resistance drop in a ansformer is the ratio of the internal resistance drop at 75 deg. cent. to the condary terminal voltage expressed in per cent.

***6051. Per cent. reactance drop.** The per cent. reactance drop in a ansformer is the ratio of the internal reactance drop to the secondary rminal voltage expressed in per cent.

***6052. Per cent. impedance drop.** The per cent. impedance drop in transformer is the ratio of the internal impedance drop at 75 deg. cent. to e secondary terminal voltage expressed in per cent.

* The internal drop in a transformer is the sum of the primary drop (reiced to secondary terms) and the secondary drop.

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6053. Regulation of constant-potential transformer. In constant-potential transformers, the regulation is the difference between the no-load and rated-load values of the secondary terminal voltage at the specified power factor (with constant primary impressed terminal voltage) expressed in per cent. of the rated-load secondary voltage, the primary voltage being adjusted to such a value that the apparatus delivers rated output at rated secondary voltage. See Par. **2390.**

Ambient temperature. See Par. **3000.**

RATING

General

6201.* **Table 601. Limiting observable temperatures and temperature rises for transformers using Class A* insulation**

	Air† cooled and air blast	Oil cooled	Water cooled
Limiting observable temperature	95 deg. cent.	95 deg. cent.	80 deg. cent.
Standard ambient temperature	40 deg. cent.	40 deg. cent.	25 deg. cent.
Limiting observable temperature rise	**55 deg. cent.**	**55 deg. cent.**	**55 deg. cent.**

The temperature of the windings of transformers is always to be ascertained by Method 2.

6202. Limiting observable temperature of oil (from Par. **2222**). The oil in which apparatus is permanently immersed shall, in no part, have a temperature, observable by thermometer, in excess of 90 deg. cent.

Permissible temperatures of insulations of more than one class. See Par. **2104.**

Temperatures of metallic parts of transformers. See Par. **2116.**

Protection against short circuit. See Par. **2120.**

Nominal rating of railway substation transformers. See Par. **2197.**

Expression of rating. See Par. **2202.**

Institute rating. See Par. **2204.**

6204. Rating of protective reactors. Protective reactors shall be rated by the following characteristics:

(*a*) Kilovolt-amperes absorbed by normal current.

(*b*) Normal current, frequency and line (delta) voltage.

(*c*) Current which the device is required to stand under short circuit conditions.

Ambient Temperature of Reference

Ambient temperature of reference for air. See Par. **2211.**

Ambient temperature of reference for water-cooled transformers. See Par. **2212.**

Transformers cooled by other means. See Par. **2213.**

Outdoor transformers exposed to sun's rays. See Par. **2214.**

Altitude Correction

Altitude. See Par. **2215.**

6215. Exception to "altitude." See Par. **2215.** Water-cooled and immersed transformers are exempt from this reduction.

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* For cotton, silk, paper and similar materials when neither treated, impregnated nor immersed in oil, the limits of the observable temperature rise shall be 15 deg. cent. below the limits fixed for these materials when impregnated.

† For exceptions in the case of air blast transformers, see Par. **6220** (*b*).

** Reactors shall be so designed as to be capable of withstanding the sudden application, without mechanical injury, of rated current at normal frequency.

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Units in Which Rating Shall be Expressed

6221. Rating of transformers. The rating of transformers shall be pressed in kilovolt-amperes (kv-a.) available at the output terminals, at specified frequency and voltage.

6222. Rating of other stationary induction apparatus. Other stationary induction apparatus such as auto-transformers, regulators, reactors, .., shall have their ratings appropriately expressed. It is also essential specify the voltage and frequency of the circuits on which the apparatus ay be used.

Kinds of Rating

Continuous rating. See Par. **2220.**
Short-time rating. See Par. **2221.**
Duty-cycle operation. See Par. **2222.**
Standard short-time ratings. See Par. **2223.**
A. I. E. E. and I. E. C. ratings. See Par. **2224.**
Continuous rating implied. See Par. **2225.**

6226. Nominal ratings. Nominal ratings are ratings which do not conm with Pars. **2220** and **2221.** They are sometimes used for railway subation transformers carrying traction loads. Transformers with nominal ting shall be capable of operating under the conditions enumerated in r. **5201.**

Rating by Temperature Rise

Permissible temperature rises for various ambient temperatures ove standard. See Par. **2231** (*d*).

TESTS

Ambient Temperature

Measurement of ambient temperatures during tests of transrmers. See Par. **2300.**

6300. Measurement of the ambient temperature during tests of ater-cooled transformers. The temperature rise of water-cooled transrmers shall be based entirely upon the temperature of the cooling water d it is not necessary to take into account the heat carried off by the air, less it exceeds the amount specified below. If under assumed standard nditions of water at 25 deg. cent., and air at 40 deg. cent., the amount heat which would be carried off by the air is 15 per cent. or more of the tal, the temperature of the cooling water, during test, should be maintained thin 5 deg. cent. of that of the surrounding air. Where this is impractible the ambient temperature should be determined from the change in e resistance of the windings, using a disconnected transformer, supplied th the normal amount of cooling water, until the temperature of the windgs has become constant.
Oil cup. See Par. **2301.**

Transformer Temperatures

Temperature rise for any ambient temperature. See Par. **2310.**
Correction for the duration of the ambient temperature of the oling medium, at the time of the heat test, from the standard nbient temperature of reference. See Par. **2311.**

***6311. Correction for the deviation of the ambient temperature the cooling medium, at the time of the heat test of air-blast transrmers from the standard ambient temperature of reference.** A rrection shall be applied to the observed temperature rise of the windings

* Thus, a cooling-air room temperature of 30 deg. cent. would correspond an inferred absolute temperature of 264.5 deg. on the scale of copper sistivity, and the correction to 40 deg. cent. (274.5 deg. inferred absolute mperature) would be 274.5/264.5 = 1.04, making the correction factor 04; so that an observed temperature rise of say 50 deg. cent. at the testing nbient temperature of 30 deg. cent. would be corrected to 50 × 1.04 = 52 g. cent., this being the temperature rise which would have occurred had e test been made with the standard ingoing cooling-air temperature of) deg. cent.

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of air-blast transformers due to difference in resistance, when the temperature of the ingoing cooling air differs from that of the standard of reference. This correction shall be the ratio of the inferred absolute ambient temperature of reference to the inferred absolute temperature of the ingoing cooling air, *i.e.*, the ratio $274.5/(234.5 + t)$; where t is the ingoing cooling-air temperature.

Duration of temperature test of transformers for continuous service. See Par. **2312.**

Duration of temperature test of transformer with a short-time rating. See Par. **2313.**

Duration of temperature test for transformer having more than one rating. See Par. **2314.**

Temperature measurements during heat run. See Par. **2315.**

6317. Methods of loading transformers for temperature tests. *General:* Whenever practicable, transformers should be tested under conditions that will give losses approximating as nearly as possible to those obtained under normal or specified load conditions, maintained for the required time. The maximum temperature rises measured during this test should be considered as the observable temperature rises for the given load. See Pars. **2312** to **2314.**

An approved method of making these tests is the *loading-back* method. The principal variations of this method are given in Par. **6317** (*b*), (*c*) and (*d*).

(*b*) *Loading-back with duplicate single-phase transformers:* Duplicate single-phase transformers may be tested in banks of two, with both primary and secondary windings connected in parallel. Normal magnetising voltage should then be applied and the required current circulated from an auxiliary source. One transformer can be held under normal voltage and current conditions while the other may be operating under slightly abnormal conditions.

(*c*) *Loading-back with one three-phase transformer:* One three-phase transformer may be tested in a manner similar to Par. **6317** (*b*) provided the primary and secondary windings are each connected in delta for the test. Normal three-phase magnetising voltage should be applied and the required current circulated from an auxiliary single-phase source.

(*d*) *Loading-back with three single-phase transformers:* Duplicate single-phase transformers may be tested in banks of three in a manner similar to that described in Par. **6317** (*c*), by connecting both primary and secondary windings in delta, applying normal three-phase magnetising voltage and circulating the required current from an auxiliary single-phase source.

(*e*) *Other methods:* Among other methods that have a limited application and can be used only under special conditions may be mentioned.

Applying dead load by means of some form of rheostat.

Running alternately for certain short intervals of time on open circuit and then on short circuit, alternating in this way until the transformer reaches a steady temperature. In this test, the voltage for the open-circuit interval and the current for the short-circuit interval shall be such as to give the same integrated core loss, and the same integrated copper loss as normal operation.

6320. Method of temperature measurement. (*a*) *Description:* The temperature of transformer windings shall be measured by their increase in resistance, corrected to the instant of shut-down when necessary, and by thermometers. Whichever measurement yields the higher temperature that temperature shall be taken as the highest observable temperature by Method 2.

(*b*) In the case of air-blast transformers, it is important to have the thermometers well distributed and in good contact with the coils, and it is especially important to note the temperature near the air outlet. In measuring the temperature of air-blast transformers, the air supply shall be shut off immediately at the end of the temperature run and the air intake closed to prevent further admission of cooling air. With the above procedure, the observable temperature rise for air-blast transformers may attain a value not in excess of 60 deg. cent. as determined by thermometer, although it must not exceed 55 deg. cent. as determined by resistance.

(*c*) *Temperature correction for cooling of transformer windings after shut-down:* Since a drop in temperature occurs in a winding between the instant of shut-down and the time of measuring the hot resistance, a correction shall be applied to the temperature determined from this measurement so as

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tain, as nearly as practicable, the temperature at the instant of shut-down. his correction may be determined approximately by plotting a time-temrature curve with temperatures as ordinates and times as abscissæ and tra-polating back to the instant of shut-down.

In cases where successive measurements show increasing temperatures :er shut-down the highest value shall be taken.

In certain cases, however, other correction factors may be applied as lows:

Oil-immersed transformers: For the purpose of simplifying the applica-n of the rule to transformers when the weight of copper in each winding is own and the copper loss as determined by wattmeter measurement does t exceed 30 watts per lb., the extrapolation method has been reduced to e following form which is recommended on account of the greater accuracy tainable under ordinary conditions of testing. The correction in degrees ntigrade shall be the product of the watts loss per pound of copper for ch winding multiplied by a factor depending upon the time elapsed between ut-down and the time of the temperature reading as given in the following ble:

Time in minutes	Factor
1	0.19
2	0.32
3	0.43
4	0.50

For intermediate times, the value of the factor can be obtained by terpolation.

When the copper loss, measured by wattmeter, does not exceed 7 watts r lb. an arbitrary correction of one degree per minute may be used provided the time elapsed between the instant of shut-down and the measurement of the hot resistance does not exceed 4 minutes.

For determining the copper loss in watts per lb., the total loss in both indings as measured by the wattmeter should be apportioned between the gh- and low-voltage windings in the same ratio as their respective I^2R sses.

Air-blast transformers: An arbitrary correction of one degree per minute ay be used provided the time elapsed between the instant of shut-down id the measurement of the hot resistance does not exceed 4 minutes.

(*d*) *Covering of thermometers:* Thermometers used for taking the tempera-re of air-cooled or air-blast transformers shall have their bulbs covered r protection from air currents. This shall be done by felt pads, approxiately 4 cm. × 5 cm. (1½ in. × 2 in.) and 3 mm. (⅛ in.) thick, except that here pads are inconvenient, as in ventilating ducts between coils, grooved ooden sticks may be used.

Temperature coefficient of copper. See Par. **2321.**

Efficiency

Efficiencies recognized. See Par. **2331.**

Normal conditions for efficiency tests. See Par. **2332.**

Direct measurement of efficiency. See Par. **2333.**

6334. Classification of losses. (*a*) *General:* Losses are classified as own below.

(*b*) *No-load losses:* No-load losses include the core loss, the I^2R loss due the exciting current and the dielectric loss in the insulation.

(*c*) *Load losses:* Load losses include I^2R losses, and stray load-losses due eddy-currents caused by fluxes varying with load.

6335. Losses to be considered in transformers. Conventional effiencies shall be based upon the losses listed in Par. **6334** and these losses all be measured as specified in Pars. **6336** and **6337.**

6336. No-load losses. The no-load losses shall be measured with open econdary circuit at the rated frequency, and with an applied primary voltge giving the rated secondary voltage plus the IR drop which occurs in e secondary under rated load conditions.

6337. Load losses. The load losses include I^2R and stray load-losses. hey shall be measured by applying a primary voltage, at rated frequency, afficient to produce rated load current in the windings, with the secondary indings short-circuited.

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Wave Shape

Standard wave shape. See Par. 2340.

Tests of Dielectric Strength

Condition of transformers to be tested. See Par. 2350.
Where high-voltage tests are to be made. See Par. 2351.
Temperature at which high-voltage tests are to be made. See Par. 2352.
Points of application of voltage. See Par. 2353.
Frequency and wave form of test voltage. See Par. 2354.
Duration of application of test voltage. See Par. 2355.

6356. Standard test voltage (from Par. 2356). *General:* The standard test voltage for all machines, except as otherwise specified, shall be twice the normal voltage of the circuit to which the machine is connected plus 1,000 volts. See exception Par. 6361.

6360. Transformers for star connection. Transformers which may be used in star connection on three-phase circuits shall be tested on the basis of the line to line voltage for which they are rated. See Par. 6361-f.

***6361. Exceptions to standard test voltage given in Section 6356.** (a) *Distributing transformers:* Transformers for primary pressures from 550 to 4,500 volts, the secondaries of which are directly connected to consumers' circuits and commonly known as distributing transformers, shall be tested with 10,000 volts from primary to core and secondary combined. The secondary windings shall be tested with twice their normal voltage plus 1,000 volts.

(b) *Auto-transformers:* Auto-transformers used for starting purposes, shall be tested with the same voltage as the test voltage of the apparatus to which they are connected.

(c) *Household devices:* Transformers taking not over 660 watts and intended solely for operation on supply circuits not exceeding 275 volts, shall be tested with 900 volts.

*(d) *Transformers for use on circuits of 25 volts or lower:* Transformers for use on circuits of 25 volts or lower, such as bell-ringing apparatus, shall be tested with 500 volts.

(e) *Alternating-current transformers connected to permanently grounded single-phase systems, for use on permanently grounded circuits of more than 300 volts:* Transformers used under these conditions shall be tested with 2.75 times the voltage of the circuit to ground plus 1,000 volts. This does not refer to three-phase transformers operating with grounded neutral.

(f) *Transformers to be used on star-connected three-phase circuits:* Transformers which may be used in star connection on three-phase circuits shall have the fine to line (as distinguished from line to neutral) voltage of the circuits on which they may be used indicated on the rating plate and the test shall be based on the line to line voltage. See Par. 6360.

(g) *Protective reactors:* Protective reactors shall be tested from conductors to ground with 2,000 volts plus 2¼ times the line voltage.

†**6362. Testing transformers by induced voltage.** Under certain conditions it is permissible to test transformers by inducing the required voltage in their windings in place of using a separate testing transformer. By "required voltage" is meant a voltage such that the line end of the windings shall receive a test to ground equal to that required by the general rules.

6363. Transformers with graded insulation. Where transformers have graded insulation they shall be so marked. They shall be tested by inducing the required test voltage in the transformer and connecting the successive line leads to ground.

Transformer windings permanently grounded within the transformer shall be tested by inducing the required test voltage in such windings. See Par. 6361.

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* This rule does not include bell-ringing transformers of ratio 125 to 6 volts.

† This test can be made by connecting the windings of two or more transformers in series, with one end of the series grounded and a voltage impressed such as will give the test from the free end to ground required by the above rule.

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Use of voltmeter and spark-gaps in dielectric tests. See Par. **2359.**
Use of spark-gap with transformers of low capacitance. See Par. **60.**
Use of spark-gap with transformers of high capacitance. See Par. **61.**
Measurements with voltmeter. See Par. **2362.**
Measurements with spark-gap. See Par. **2363.**

Regulation

Conditions for tests of regulation. See Par. **2390.**

6390. Conditions for tests of regulation. (*a*) *Frequency:* The regulation of transformers is to be determined at constant frequency.
(*b*) *Power factor:* In transformers, the power factor of the load to which the regulation refers should be specified. Unless otherwise specified, it shall be understood as referring to non-inductive load, that is, to a load in which the current is in phase with the e.m.f. at the output side of the transformer. See Par. **2390.**

***6391. Tests and computation of regulation.** (*a*)* *Method I. By loading:* The regulation of a constant potential transformer can be determined by loading the transformer and measuring the change in voltage with change in load, at the specified power factor.
(*b*) *Method II. From impedance watts and volts:* The regulation of a constant potential transformer for any specified load and power factor can be computed from the measured impedance watts and impedance volts as follows:

Let:

P = impedance watts, as measured in the short-circuit test and corrected to 75 deg. cent.
E_s = impedance volts, as measured in the short-circuit test.
IX = reactance drop in volts.
I = rated primary current.
E = rated primary voltage.
q_r = per cent. drop in phase with current.
q_s = per cent. drop in quadrature with current.

$$IX = \sqrt{E_s^2 - \left(\frac{P}{I}\right)^2}$$

$$q_r = 100\frac{P}{EI}$$

$$q_s = 100\frac{IX}{E}$$

Then—
For *unity power factor*, we have approximately,

$$\text{Per cent. regulation} = q_r + \frac{q_s^2}{200}$$

For *inductive loads* of power-factor m and reactive-factor n,

$$\text{Per cent. regulation} = mq_r + nq_s + \frac{(mq_s - nq_r)^2}{200}$$

CONSTRUCTION

Rating Plates

Marking of rating plates. See Par. **2401.**

Transformer Connections

(*These rules do not apply to auto-transformers*)

General

†**6402. Scope.** These rules specify the markings of leads brought out of the case but not the markings of winding terminals inside of the case, ex-

* This method is not generally applicable for shop tests, particularly on large transformers.
† It is recognised that special cases will arise from time to time that these rules will not cover and that it would be very difficult to cover by any set of general rules.

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cept that these terminals shall be marked with numbers in any manner that will permit of convenient reference and that cannot be confused with the markings of the leads brought out of the case.

TRANSFORMER LEAD MARKINGS SINGLE PHASE TRANSFORMERS

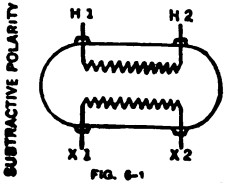


FIG. 6-1

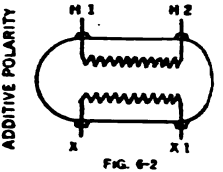


FIG. 6-2

Simple High and Low-Voltage Windings Without Taps

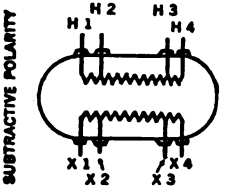


FIG. 6-5

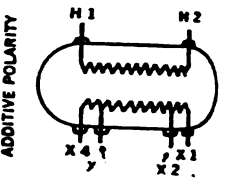


FIG. 6-4

Simple High and Low-Voltage Windings With Taps

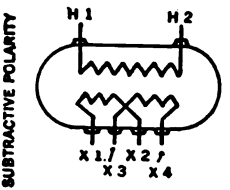


FIG. 6-3

Series Multiple Low-Voltage Winding Without Taps

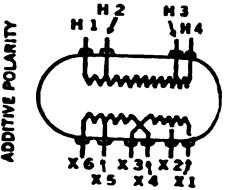


FIG. 6-6

Series Multiple Low-Voltage Winding With Taps

NOTE:—The above figures illustrate the application of the rules on lead markings to transformers having subtractive and additive polarity.

***6403. Markings of leads.** (*a*)* *General:* The leads shall be distin-

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* By "tertiary winding" is meant a third winding that, compared with both of the other two windings, has smaller kilovolt-ampere rating than either or, if the kilovolt-ampere rating is the same as one or both of the other two, has lower voltage. *E.g.*, if a transformer has three separate windings, one for 1,000 kv-a., 33,000 volts, one for 600 kv-a., 550 volts and one for 400 kv-a. 6,600 volts, the 400 kv-a. winding is the teritary winding; or, if a transformer has three separate windings each with a capacity of 1,000 kv-a., and with voltages of 33,000, 6,600 and 550 respectively, the 550 volt winding is the tertiary winding.

According to this definition neither one of two similar windings arranged for series-parallel connection is to be classed as a tertiary winding.

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ıished from one another by marking each lead with a capital letter followed y a number. The letters to be used are: *H* for high-voltage leads, *X* for w-voltage leads and *Y* for tertiary winding leads. The numbers to ɜed are 1, 2, 3, etc.

*(*b*) *Neutral lead:* A neutral lead shall be marked with the proper letter llowed by *O*, *e.g.*, *HO*, *XO*.

6404. Diagrammatic sketch of connections. The manufacturer shall ırnish with each transformer a complete diagrammatic sketch showing ıe leads and internal connections and their markings and the voltages ɔtainable with the various connections.

This sketch should preferably be on a metal plate attached to the transrmer case.

Single-phase Transformers

6405. Order of numbering leads in any winding. The leads of any inding (high-voltage, low-voltage or tertiary) brought out of case shall be umbered 1, 2, 3, 4, 5, etc., the lowest and highest numbers marking the ill winding and the intermediate numbers marking fractions of winding or ıps. All numbers shall be so applied that the potential difference from ay lead having a lower number toward any lead having a higher number ıall have the same sign at any instant.

If a winding is divided into two or more parts for series parallel connecons, and the leads of these parts are brought out of case, the above rule ıall apply for the series connection with the addition that the leads of each ortion of winding shall be given consecutive numbers. See Figs. 6-5 and -6.

6406. Relation of order of numbering leads of different windings. he numbering of the high-voltage and low-voltage leads shall be so applied ıat when H_1 and X_1 are connected together and voltage applied to the transrmer, the voltage between the highest numbered *H* lead and the highest umbered *X* lead shall be less than the voltage of the full high-voltage inding.

The same relation shall apply between high-voltage and tertiary and lowoltage and tertiary winding.

6407. Polarity. When leads are marked in accordance with the above ıles, the polarity of a transformer is

Subtractive when H_1 and X_1 are adjacent. See Figs. 6-1, 6-3 and 6-5.

Additive when H_1 is diagonally located with respect to X_1. See Figs. 6-2, -4 and 6-6.

6408. Location of H_1 lead. To simplify the work of connecting transrmers in parallel it is recommended that the H_1 lead shall be brought out n the right hand side of the case, facing high-voltage side of the case.

†**6409. Parallel operation.** Transformers having leads marked in ccordance with these rules may be operated in parallel by connecting simarly marked leads together, provided their ratio, voltages, resistances and eactances are such as to permit parallel operation.

Three-phase Transformers

6410. Marking of full winding leads. The three high-voltage leads nd the three low-voltage leads which connect to the full-phase windings, ıall be marked H_1, H_2, H_3, and X_1, X_2, X_3. The full-phase winding of a ertiary winding shall be marked Y_1, Y_2, Y_3.

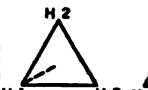
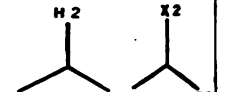
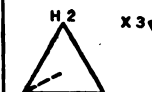
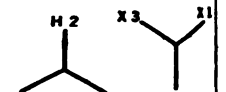
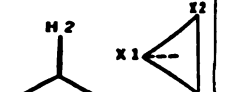
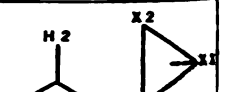
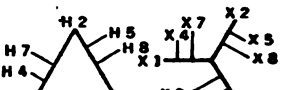
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* A lead brought out from the middle of a winding for some other use, than ıat of neutral lead, *e.g.*, a 50 per cent. starting tap, shall be marked as a ap lead.

† In some cases design may be such as to permit parallel operation, lthough due to the difference in the number of tap leads, the leads to be onnected together may not have the same number.

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Transformer lead markings and voltage vector diagrams for the usual three-phase transformer connections

	THREE PHASE TRANSFORMERS WITHOUT TAPS	
GROUP-1 ANGULAR DISPLACEMENT 0°	 FIG. 6-7	 FIG. 6-8
GROUP-2 ANGULAR DISPLACEMENT 180°	 FIG. 6-9	 FIG. 6-10
GROUP-3 ANGULAR DISPLACEMENT 30°	 FIG. 6-11	 FIG. 6-12
	 FIG. 6-13	 FIG. 6-14
	THREE PHASE TRANSFORMERS WITH TAPS	
GROUP-3 ANGULAR DISPLACEMENT 30°	 FIG. 6-15	

NOTE.—The above figures are included to illustrate the method of marking transformer leads that are brought out of the case and are not intended to standardize connections, vector diagrams or polarity.

***6411. Relation between high-voltage and low-voltage windings.** (*a*) *General:* The markings shall be so applied that if the phase sequence of voltage on the high-voltage side is in the time order H_1, H_2, H_3 it is in the time order of, X_1, X_2, X_3 on the low-voltage side and Y_1, Y_2, Y_3 for a tertiary winding.

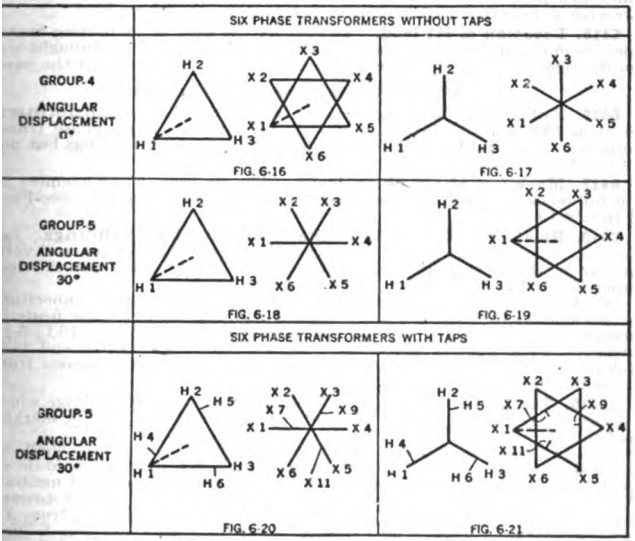
*(*b*) *Angular displacement:* In order that the markings of lead connections between phases shall indicate definite phase relations, they shall be made in

* Any three-phase transformer having a delta Y connection may be represented by voltage vector diagram either in accordance with Fig. 6-11 or

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ccordance with one of the three three-phase groups as shown. The angular splacement between the high-voltage and low-voltage windings is the angle each of the voltage vector diagrams (Figs. 6-7 to 6-14 inclusive) between ie lines passing from its neutral point through H_1 and X_1 respectively.

ransformer lead markings and voltage vector diagrams for the usual six-phase transformer connections



NOTE.—The above figures are included to illustrate the method of mark- ig transformer leads that are brought out of the case and are not intended) standardize connections, vector diagrams or polarity.

6412. Tap leads. (*a*) *General:* Where tap leads are brought out of the ase (neutral lead excepted) they shall be marked with the proper letter llowed by the numbers 4, 7, etc., for one phase 5, 8, etc., for another hase and 6, 9, etc., for the third phase. See Fig. 6-15.

(*b*) *Delta connection:* The order of numbering tap leads shall be as follows: , 7, etc., from lead 1 toward lead 2; 5, 8, etc., from lead 2 toward lead 3; nd 6, 9, etc., from lead 3 toward lead 1. See Fig. 6-15.

(*c*) *Star connection:* The order of numbering tap leads shall be as follows: , 7, etc., from lead 1 toward neutral; 5, 8, etc., from lead 2 toward neutral; nd 6, 9, etc., from lead 3 toward neutral. See Fig. 6-15.

6413. Interphase connection made outside of case. Where the nterphase connections are made outside of case, the leads shall be marked rith the proper letter followed by the numbers 1, 4, 7, 10, etc., for one phase; , 5, 8, 11, etc., for the second phase; and 3, 6, 9, 12, etc., for the third phase.

ig. 6-13. Any three-phase transformer having Y delta connection may be epresented by voltage vector diagram either in accordance with Fig. 6-12 r Fig. 6-14. Since these voltage vector diagrams are equivalent, it is recom- nended that the terminal markings for three-phase transformers having elta Y connection be always made in accordance with Fig. 6-11 and that he terminal markings for three-phase transformers having Y delta connec- ion be always made in accordance with Fig. 6-12.

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The markings shall be so applied that when a star connection is made by joining together the highest numbered leads of each phase, all rules here given, excepting Par. **6408** (*b*) apply.

***6414. Parallel operation.** Transformers having leads marked in accordance with these rules may be operated in parallel by connecting similarly marked leads together provided their angular displacements are the same and provided also their ratios, voltages, resistances, and reactances are such as to permit parallel operation.

6415. Location of H1 lead. To simplify the work of connecting transformers in parallel it is recommended that the *H*1 lead shall be brought out on the right hand side of the case, facing the high-voltage side of the case.

Three-phase to Six-phase Transformers

6416. Rules that are applicable for three-phase transformers. Sections **6411** (*b*) and **6412** shall apply to three-phase to six-phase transformers. Rules **6410** and **6412** shall apply to three-phase windings but not to six-phase windings.

6417. Markings of six-phase leads. The six leads which connect to the full-phase windings shall be marked *X*1, *X*2, *X*3, *X*4, *X*5, *X*6. See Figs. 6-16 to 6-19 inclusive.

6418. Relation between three-phase and six-phase windings. (*a*) *General:* The markings shall be so applied that if the phase sequence of voltage on the three-phase side is in the time order *H*1, *H*2, *H*3, it is in the time order of *X*1, *X*2, *X*3, *X*4, *X*5, *X*6 on the six-phase side.

(*b*) *Angular displacement:* In order that the markings of lead connections between phases shall indicate definite phase relations, they shall be made in accordance with one of the four six-phase groups shown in Figs. 6-16 to 6-19 inclusive. The angular displacement between the high-voltage and low-voltage windings is the angle in each of the voltage vector diagrams from its neutral through *H*1 and *X*1 respectively.

†**6419. Tap leads.** (*a*) *General:* Where tap leads from low-voltage windings are brought out of the case (neutral lead excepted), they shall be marked as follows:

(*b*) *Diametrical connection:* Diametrical connection tap leads shall be marked from the two ends of each phase winding toward the middle or neutral point in the following order: *X*7, *X*13, etc., from *X*1 toward neutral; *X*8, *X*14, etc., from *X*2 toward neutral; *X*9, *X*15, etc., from *X*3 toward neutral; *X*10, *X*16, etc., from *X*4 toward neutral; *X*11, *X*17, etc., from *X*5 toward neutral; *X*12, *X*18, etc., from *X*6 toward neutral. See Fig. 6-20.

A tap from the middle point of any phase winding, not intended as a neutral, shall be given a number determined by counting from *X*1, *X*2 or *X*3 and not from *X*4, *X*5, or *X*6; *e.g.*, if the only taps brought out are 50 per cent. starting taps, they shall be numbered *X*7, *X*8, and *X*9.

†(*c*) *Double-delta connection:* Tap leads shall be marked in the following order: *X*7, *X*13, etc., from *X*1 toward *X*3; *X*8, *X*14, etc., from *X*2 toward *X*4; *X*9, *X*15, etc., from *X*3 toward *X*5; *X*10, *X*16, etc., from *X*4 toward *X*6; *X*11, *X*17, etc., from *X*5 toward *X*1; *X*12, *X*18, etc., from *X*6 toward *X*2. See Fig. 6-21.

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Associasone Elettrotecnica Italiana: Norme per l'ordinasione e il collaudo delle Macchine Elettriche.

* In some cases designs may be such as to permit parallel operation although, due to a difference in the number of tap leads, the leads to be connected together are not similarly marked.

† For starting purposes it is generally customary to bring out only two taps from one delta and start three-phase.

British Electrical and
British Engineering Standard
for Electrical Machinery (exc
Société Internationale des
Union des Syndicats de
Fourniture et la Réception de
Verband Deutscher Elek
Leitsätse.

International Electrotechnic

C

STANDARDS FOR PROTE

The A. I. E. E. Standards f
are the general standards sh
in other chapters which are
with the modifications and e

*7000. **Switching and c**
standardization rules switchi
apparatus whose function is
termined manner electric app

7001. **Switch.** A switch
the connections in an electric

7002. **Master-switch.** A
govern the operation of co
controller.

7003. **Control switch.**
electrically-operated switches

7004. **Auxiliary switch.**
some main device, for signall

7005. **Circuit breaker.**
fuse) constructed primarily f
abnormal conditions.

7006. **Contactor.** A co
and interrupting an electric

†7007. **Electric controlle**
of devices, which is designed
operation of the apparatus t

‡7008. **Motor-starter.**
for accelerating a motor to n

7009. **Automatic motor**
motor-starter designed to au

7010. **Auto-transformer**
starter is a motor-starter ha
voltage for starting. The d
nism, and is frequently calle

* The "National Electrical
tion deals with certain circu
and fuses up to 600 volts ra
† A switch (see Par. 7001)
‡ A device designed for st
called a controller (see Par.

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British Electrical and Allied Manufacturers' Association: Reports
ritish Engineering Standards Association: British Standardisation Rules
r Electrical Machinery (except motors for traction purposes).
Société Internationale des Electriciens: Bulletins.
Union des Syndicats de l' Electricité: Instructions générales pour la
ourniture et la Réception des Machines électriques.
Verband Deutscher Elektro-techniker: Normalien, Vorschriften und
itsätze.

International

International Electrotechnical Commission: Rating of Electrical Machinery.

CHAPTER VII

STANDARDS FOR SWITCHING, CONTROL AND PROTECTIVE APPARATUS

The A. I. E. E. Standards for switching control and protective apparatus
e the general standards shown in Chapters II and III and the standards
other chapters which are applicable to the devices involved, together
th the modifications and extensions given in this chapter.

DEFINITIONS

Devices

7000. Switching and control apparatus. For the purpose of these
ndardization rules switching and control apparatus is defined as electric
paratus whose function is primarily to control or protect in some prede-
mined manner electric apparatus to which it is connected.

7001. Switch. A switch is a device for making, breaking or changing
connections in an electric circuit.

7002. Master-switch. A master-switch is a switch which serves to
vern the operation of contactors and auxiliary devices of an electric
ntroller.

7003. Control switch. A control switch is a switch for controlling
ctrically-operated switches and circuit breakers.

7004. Auxiliary switch. An auxiliary switch is a switch actuated by
ne main device, for signalling, interlocking, etc.

7005. Circuit breaker. A circuit breaker is a device (other than a
e) constructed primarily for the interruption of a circuit under *infrequent*
normal conditions.

7006. Contactor. A contactor is a device for repeatedly establishing
d interrupting an electric circuit under normal conditions.

7007. Electric controller. An electric controller is a device, or group
devices, which is designed to control in some predetermined manner the
eration of the apparatus to which it is connected.

7008. Motor-starter. A motor-starter is an electric controller designed
accelerating a motor to normal speed in one direction of rotation.

7009. Automatic motor-starter. An automatic motor-starter is a
tor-starter designed to automatically control the acceleration of a motor.

7010. Auto-transformer motor-starter. An auto-transformer motor-
rter is a motor-starter having an auto-transformer to furnish a reduced
tage for starting. The device includes the necessary switching mecha-
m, and is frequently called a compensator or auto-starter.

The "National Electrical Code" of the National Fire Protection Associa-
deals with certain circuit breakers up to 550 volts rating and switches
fuses up to 600 volts rating fuses.
A switch (see Par. 7001) should not be called a controller.
A device designed for starting a motor in either direction of rotation is
ed a controller (see Par. 7007).

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*7015. **Fuse.** A fuse is an element designed to melt or dissipate at a predetermined current value, and intended to protect against abnormal conditions of current.

7016. **Relay.** A relay is a device by means of which contacts in one circuit are operated by change in conditions in the same or other circuits.

7018. **Rheostat.** A rheostat is a resistor which is provided with means for readily varying its resistance See Par. 3064.

7019. **Protective reactor.** A protective reactor (see Par. 3078) is a device for protecting circuits by limiting the current flow and localizing the disturbance under short-circuit conditions.

*7020. **Lightning arrester.** A lightning arrester is a device for protecting circuits and apparatus against lightning or other abnormal potential rises of short duration.

7021. **Under-voltage or low-voltage release switching and control apparatus.** Under-voltage or low-voltage release switching and control apparatus is apparatus which, on the reduction or failure of voltage, operates to cause the interruption of power to the main circuit, but which does not prevent the re-establishment of the main circuit on return of voltage.

7022. **Under-voltage or low-voltage protection switching and control apparatus.** Under-voltage or low-voltage protection switching and control apparatus is apparatus which, on the reduction or failure of voltage, operates to cause and maintain the interruption of power to the main circuit.

7023. **Phase-failure protection switching and control apparatus.** Phase-failure protection switching and control apparatus is apparatus which, on the failure of power in one wire of a polyphase circuit, operates to cause and maintain the interruption of power on the circuit.

7024. **Phase-reversal protection switching and control apparatus.** Phase-reversal protection switching and control apparatus is apparatus which, on the reversal of the phase relations in a polyphase circuit, operates to cause and maintain the interruption of power on the circuit.

Characteristics of Devices

7030. **"Air" as a prefix.** The prefix "air" applied to a device which interrupts an electric circuit indicates that the interruption occurs in air.

7031. **"Oil" as a prefix.** The prefix "oil" applied to a device which interrupts an electric circuit indicates that the interruption occurs in oil.

7032. **Fume-resisting.** Fume-resisting switching and control apparatus is apparatus so constructed that it will not be readily injured by the specified fumes.

‡7033. **Drip-proof.** Drip-proof switching and control apparatus is apparatus so protected as to exclude falling moisture or dirt.

7034. **Dust-proof.** Dust-proof switching and control apparatus is apparatus so constructed or protected that the accumulation of dust within or without the device will not interfere with its successful operation.

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* Any terminals, tubes, etc., integral with this element are included as part of the fuse.

Fuses may be divided into two classes:

(*a*) Those designed to protect the circuit and apparatus both against short-circuit and against definite amounts of overload (*e.g.*, fuses of the National Electric Code which open on 25 per cent. overload).

(*b*) Those designed to protect the system only against short-circuits (*e.g.* expulsion fuses, which blow at several times the current which they are designed to carry continuously). The line separating these two classes is not definitely fixed.

† Lightning arresters may be divided into two classes:

(*a*) Those intended to discharge for a very short time.

(*b*) Those intended to discharge for a period of several minutes.

‡ Drip-proof apparatus may be either open or semi-enclosed, if it is provided with suitable protection integral with the apparatus, or so enclosed as to exclude effectively falling solid or liquid material.

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7035. Dust-tight. Dust-tight switching and control apparatus is apparatus so constructed that the dust will not enter the enclosing case.

7036. Explosion-proof. Explosion-proof switching and control apparatus is apparatus so constructed that explosions of gas within the casing will not injure it or ignite inflammable gas outside it.

7037. Gas-proof. Gas-proof switching and control apparatus is apparatus so constructed or protected that the specified gas will not interfere with its successful operation.

7038. Gas-tight. Gas-tight switching and control apparatus is apparatus so constructed that the specified gas will not enter the enclosing case.

7039. Moisture-resisting. Moisture-resisting switching and control apparatus is apparatus so constructed or treated that it will not be readily injured by moisture. (Such apparatus shall be capable of operating in a very humid atmosphere, such as found in mines, evaporating rooms, etc.)

7040. Splash-proof. Splash-proof switching and control apparatus is apparatus so constructed or protected that external splashing will not interfere with its successful operation.

7041. Submersible. Submersible switching and control apparatus is apparatus so constructed that it will operate successfully when submerged in water under specified conditions of pressure and time.

7042. Sleet-proof. Sleet-proof switching and control apparatus is apparatus so constructed or protected that the accumulation of sleet will not interfere with its successful operation.

Parts of Devices

7050. Conducting Parts. Conducting parts of switching and control apparatus are those designed to carry current or which are conductively connected therewith.

7051. Contact. A contact is a surface common to two conducting parts, united by pressure, for the purpose of carrying current.

7052. Magnet brake. A magnet brake is a friction brake controlled by electro-magnetic means.

7053. Grounded parts. Grounded parts are those parts which may be considered to have the same potential as the earth.

Properties of Devices

7060. Interrupting rating. Interrupting (breaking or rupturing) rating is a rating based upon the r.m.s. current at normal voltage which the device can interrupt under prescribed conditions as stated intervals a specified number of times.

OPERATION

Temperature Limits

7101. Circuit breakers, relays and switches. The maximum observable temperature rises of the various parts of circuit breakers, relays and switches shall not exceed the following limits for ambient temperatures up to and including but not greater than 40 deg. cent. See Par. 7301.

Contacts in air, when clean and bright	30 deg. cent.
Oil and contacts therein	30 deg. cent.
Coils, if insulation is of unimpregnated fibrous material	35 deg. cent.
Coils, if insulation is of fibrous material treated to withstand heat	50 deg. cent.
Coils, if insulation is of asbestos, mica or similar heat resisting material	70 deg. cent.

* The Institute calls attention to the inherent decrease in current which can be carried by switch and circuit breaker contacts in air, due to oxidization of the contact surfaces. The rating of air switches and circuit breakers is, therefore, based on sufficient maintenance to keep the temperature rise within the specified limits. Relays which form part of controllers are to have the temperature limits specified in Par. 7103.

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Coils on which a thermometer can be applied directly to the surface of the bare winding, such as those having bare edgewise strip conductors, shall be allowed 10 deg. cent. higher maximum observable temperature rise than permitted above for each kind of insulation.

Other parts: All other parts than those whose temperature affects the temperature of the insulating material may be operated at such temperatures as shall not be injurious in any other respect.

7102. Magnetic contactors. The maximum observable temperature rises of the various parts of magnetic contactors shall not exceed the following limits for ambient temperatures up to and including but not greater than 40 deg. cent. See Par. **7302.**

Laminated contacts	65 deg. cent.
Operating coils	70 deg. cent.
Solid contacts	100 deg. cent.
Current-carrying parts insulated with asbestos or other fireproof material	150 deg. cent.

7105. Fuses. The maximum observable temperature rise of coils or windings, measured by thermometer, shall not exceed the following limits for ambient temperatures up to and including but not greater than 40 deg. cent.

If insulation is of unimpregnated fibrous material	35 deg. cent.
If insulation is of fibrous material treated to withstand heat	50 deg. cent.
If insulation is of asbestos, mica or similar heat resisting material with a cotton binder	70 deg. cent.

7106. Cast grid resistors. The maximum observable temperature rises of cast grids used as resistors shall not exceed 350 deg. cent. for ambient temperatures up to and including but not greater than 40 deg. cent.

RATING

Expression of Rating

7201. Rating of circuit breakers and switches. The rating of a circuit breaker or switch shall include the following items:

(*a*) The normal r.m.s. current which it is designed to carry.

(*b*) The normal r.m.s. pressure (voltage) of the circuit on which it is intended to operate.

(*c*) The normal frequency of the current.

(*d*) The interrupting rating of the device. See Par. **7060.**

7202. Continuous current-carrying capacity of fuses. Fuses shall be so constructed that they will carry continuously 110 per cent. of their rated current.

7205. Rating of lightning arresters. The rating of a lightning arrester shall be the voltage of the circuit on which it is to be used.

TESTS

Heat Tests

7301. Circuit breakers, relays and switches. The rated current of circuit-breakers, relays and switches at rated frequency shall be applied continuously until the temperature becomes constant. The temperature rises measured by thermometer shall not exceed the limits specified in Par. **7101.**

7302. Magnetic contactors. The rated current of magnetic contactors at rated frequencies shall be applied continuously or until the temperature becomes constant when continuous duty is specified. It shall be applied for the specified length of time when given a short time rating. The temperature rises measured by thermometer shall not exceed the limits specified in Par. **7102.**

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* Coils or windings such as accompany fuses of the magnetic blow-out type.

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Tests of Dielectric Strength

7323. Standard test voltage. (*a*) *Apparatus rated at 600 volts or less:* The standard test voltage for all switching and control apparatus rated at 600 volts or less shall be twice the normal voltage of the circuit to which the apparatus is to be connected plus 1,000 volts.

(*b*) *Apparatus rated above 600 volts:* Apparatus rated above 600 volts shall be tested at 2¼ times rated voltage, plus 2,000 volts, at a specified altitude.*

As a supplementary test, devices for outdoor use should be capable of withstanding for 10 sec. a dielectric wet test at twice rated voltage plus 1,000 volts.

(*c*) *Auto-transformers for motor-starters:* Auto-transformers for motor-starters shall be tested with the same voltage as the test voltage of the apparatus to which they are to be connected.

Tests of Lightning Arresters

7371. Resistance. The resistance of the arrester at double potential and also at normal potential, shall be determined by observing the discharge currents through the arrester.

7372. Arrester with gap. In the case of any arrester using a gap, a test shall be made of the spark potential on either direct-current or 60-cycle alternating-current excitation.

7373. Equivalent sphere gap. The equivalent sphere gap under disruptive discharge shall be measured, using a considerable quantity of electricity.

7374. Continuous surges. The endurance of the arrester to continuous surges shall be tested.

7376. Dielectric strength. See Pars. **2355** and **7323.**

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CHAPTER VIII

STANDARDS FOR METERS, INSTRUMENTS AND INSTRUMENT TRANSFORMERS

The A. I. E. E. Standards for meters, instruments and instrument transformers are the general standards shown in Chapters II and III, and the standards in other chapters which are applicable to the devices involved, together with the modifications and extensions given in this chapter.

DEFINITIONS

†**8000. Meter.** A meter is a device which registers through a totalizing mechanism, the integral, with respect to time, of the electrical quantity to which it responds. (This definition does not preclude the general use of "meter" as a suffix or in compound words, to mean a "measuring device.")

†**8001. Instrument.** An instrument is a device which indicates or records the present value of the quantity under observation.

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* This assumes a precipitation of $\frac{1}{10}$ in. (2.54 mm.) per min. at an angle of 45 deg. from the perpendicular with water having a resistivity as low as 7,000 ohm-centimeters.

† While the word "instrument" is a general term which may properly include indicating, integrating and recording devices, there is a tendency to restrict its use to indicating devices and to recording (graphic or curve drawing) devices. Integrating devices are then denoted by the word "meter." This distinction gives rise to the above general definitions.

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8002. General nomenclature. In general, the names of meters and instruments are self-defining. The following names are preferred to others sometimes used for the same devices: Reactive-factor meter, power-factor meter, watthour meter, reactive volt-ammeter (or reactive volt-ampere indicator), etc.

8003. Recording instruments. Recording ammeters, voltmeters, wattmeters, etc., are instruments which record graphically, upon time charts, the values of the quantities they measure.

8004. Crest voltmeter. A crest voltmeter is a voltmeter depending for its indications upon the crest, or maximum value of the voltage of the system to which it is connected. Crest voltmeters shall be marked in true crest volts and also in the r.m.s. value of the sinusoidal wave having the same crest value. (See Par. **2362.**)

8005. Synchronoscope (also called a synchroscope or synchronism indicator). A synchronoscope is a device which indicates synchronism between two machines, and in addition shows whether the in-coming machine is fast or slow.

8006. Line-drop voltmeter compensator. A line-drop voltmeter compensator is a device used in connection with a voltmeter which causes the latter to indicate the voltage at some distant point of the circuit.

8007. Demand-meter. (*a*) *General:* A demand-meter is a device which indicates or records the demand or maximum demand. In practice, two types are recognised. See Pars. **3454, 3458, 3460** and **3464.**

(*b*) *Integrated-demand-meter:* An integrated-demand-meter is a demand-meter which indicates or records the maximum demand obtained through integration.

(*c*) *Lagged-demand-meter:* A lagged-demand-meter is a demand-meter in which the indication of maximum demand is subject to a characteristic time lag.

***8020. Period of an instrument.** The period of an instrument, sometimes called the "periodic time," is the time taken for the pointer to make one complete oscillation (two consecutive swings). A swing is a complete movement in either direction.

8030. Instrument transformer. An instrument transformer is a transformer suitable for use with measuring instruments; that is, one in which the conditions of phase and of current or potential in the primary circuit, are represented with acceptable accuracy in the secondary circuit. An instrument transformer may be either an instrument current transformer or an instrument potential (voltage) transformer.

***8031. Secondary burden.** The secondary burden of a current transformer is an expression in ohms and henrys of the resistance and inductance of the external circuit connected to the secondary of that transformer.

8032. Voltage ratio of instrument transformer. The voltage ratio of an instrument potential transformer is the ratio of the r.m.s. primary terminal voltage to the r.m.s. secondary terminal voltage, under specified secondary burden.

8033. Current ratio of instrument transformer. The current ratio of an instrument current transformer is the ratio of r.m.s. primary current to r.m.s. secondary current, under specified secondary burden.

8034. Marked ratio of instrument transformer. The marked ratio of an instrument transformer is the ratio which the apparatus is designed to give under average conditions of use. When a precise ratio is required, it is necessary to specify the voltage or current, frequency, load and secondary burden.

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* In strongly damped instruments, the period is influenced by the amplitude of the movement.

† Considerable uncertainty of meaning has been occasioned by the use of the terms, load, secondary load, and secondary connected load for this quantity, and such use is discouraged.

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OPERATION

8101. Permissible temperature in shunts. (*a*) *General:* The limiting servable temperature of shunts measured by Method I shall not exceed 0 deg. cent.
(*b*) *Exceptions:* The above rule shall not apply to shunts having no solred joint and made of material which is not permanently changed in resisnce if continuously subjected to a higher temperature.

8110. Grounding of meters and instruments. The covers of meters d instruments, which are used with current and potential transformers, all be connected to the grounded sides of the secondary circuits of such ansformers in all cases where the indications of the instrument are liable be influenced by electrostatic action.

8111. Instrument current transformers on open secondary circuit. nder conditions of open secondary circuit, current transformers shall be pable of carrying continuously rated primary current without damage to e primary insulation and without interruption of service.

8112. Instrument current transformers on closed secondary circuit. Under conditions of closed secondary circuit, current transformers all withstand 40 times rated current applied for 1 second, without injury.

RATING

8200. General. The rating of a meter is a designation assigned by the anufacturer to indicate its operating limitations. The full scale marking an instrument does not necessarily correspond to its rating, but if the ting differs from the full scale marking, the rating shall be marked on the strument.

8201. Standard ambient temperature. For purposes of rating meters id shunts, the standard ambient temperature shall be 40 deg. cent. See ars. **8301** and **2211.**

8202. Rating limitation of the circuits of meters and instruments. o circuit of a meter or instrument shall be given a rating higher than that rresponding to the maximum current or voltage to which it may be conuously subjected.

8203. Temperature rise of meter and instrument windings. The rmissible temperature rises in meters and instruments shall be based upon e temperatures specified in Par. **1005** and the standard ambient temperare of 40 deg. cent.

8204. Temperature rise in shunts. Shunts shall be rated in accordnce with their observable temperature rise by Method 1, assuming the timate temperatures specified in Par. **8101** and an ambient temperature ecified in Par. **8201.**

TESTS

8300. Measurement of temperature rise of shunts. Observable nperature shall be measured in such a manner as not to cause local change temperature.

8301. Standard temperature of reference for meter and instrument aracterisitcs. The standard temperature of reference for meter and trument characteristics shall be 20 deg. cent. See Pars. **8201, 2211.**

8302. Damping. The pointer being at zero before any load is applied, mping shall be measured by suddenly applying and maintaining a load ich will give a steady deflection of one-half full angular scale, and observ- the following quantities:
a) The number of swings taken by the pointer in coming to rest.
b) The time, in seconds, required for the pointer to come to rest.
c) The overshooting, in per cent. of the angular displacement due to the turbance.

Heating is frequently an immaterial consideration in determining the ng of meters and instruments. Losses, impairment of accuracy and other ors often determine the rating.

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Dielectric Strength of Instrument Transformers

8310. Test voltage instrument potential transformers. The test voltage for instrument potential transformers shall be twice the normal voltage of the circuit to which it is connected plus 1,000 volts.

8311. Test voltage of instrument current transformers. The test voltage of instrument current transformers shall be 2½ times the rated voltage plus 2,000 volts.

8312. Test voltage for meters and instruments. (The Institute is not at present in a position to make recommendations.)

SPECIFICATION OF CHARACTERISTICS

8500. Errors of indicating instruments. In specifying the accuracy of an indicating instrument, the error at any point on the scale shall be expressed as a percentage of the full scale reading.

8501. Torque. The torque of meters and instruments shall be expressed in millimeter-grams.

8502. Damping. The damping of an instrument shall be expressed in terms of the quantities enumerated in Par. **8302**, all three of which are essential to a complete description.

***8503. Marking of switchboard shunts.** The marking of switchboard shunts shall include the rating in amperes, the drop in volts at that rating, and the serial number of any instrument in connection with which the shunt may be calibrated. When shunts are designed to be used with devices taking sufficient current to be an appreciable proportion of the whole, this fact shall be indicated.

BIBLIOGRAPHY

United States

Association of Edison Illuminating Companies and National Electric Light Association: Joint Meter Code.

Bureau of Standards, Circular No. 56, entitled "Standards for Electric Service."

Foreign

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CHAPTER IX

STANDARDS FOR WIRES AND CABLES

DEFINITIONS

†**9000. Wire.** A wire is a slender rod or filament of drawn metal.

‡**9001. Conductor.** A conductor is a wire or combination of wires not insulated from one another, suitable for carrying a single electric current.

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* For example, if with 100 amperes rated load in the main circuit, a measuring device takes 10 amperes, leaving 100 less 10 amperes in the shunt with a drop of 0.050 volts, the shunt shall be marked: Volts 0.050. Amperes 100 less 10.

† The definition restricts the term to what would ordinarily be understood by the term "solid wire." In the definition, the word "slender" is used in the sense that the length is great in comparison with the diameter. If a wire is covered with insulation, it is properly called an insulated wire; while primarily the term "wire" refers to the metal, nevertheless when the context shows that the wire is insulated, the term "wire" will be understood to include the insulation.

‡ The term "conductor" is not to include a combination of conductors insulated from one another, which would be suitable for carrying several different electric currents. Rolled conductors (such as bus-bars) are, of course, conductors, but are not considered under the terminology here given.

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***9002. Stranded conductor.** A stranded conductor is a conductor mposed of a group of wires, or of any combination of groups of wires.

9003. Strand. A strand is one of the wires, or groups of wires, of any randed conductor.

†**9004. Cable.** A cable is either a stranded conductor (single-conductor able), or a combination of conductors insulated from one another (multiple-onductor cable).

‡**9005. Stranded wire.** A stranded wire is a group of small wires, used a single wire.

§**9006. Cord.** A cord is a small cable, very flexible and substantially nsulated to withstand wear.

9007. Concentric strand. A concentric strand is a strand composed a central core surrounded by one or more layers of helically-laid wires or roups of wires.

9008. Concentric-lay cable. A concentric-lay cable is a single-conduc-or cable composed of a central core surrounded by one or more layers of elically-laid wires.

‖**9009. Rope-lay cable.** A rope-lay cable is a single-conductor cable mposed of a central core surrounded by one or more layers of helically-laid roups of wires.

¶**9010. N-conductor cable.** An N-conductor cable is a combination of -conductors insulated from one another.

***9011. N-conductor concentric cable.** An N-conductor concentric able is a cable composed of an insulated central conductor with (N-1) tubu-ar stranded conductors laid over it concentrically and separated by layers f insulation.

††**9012. Duplex cable.** A duplex cable is a cable composed of two insu-ated stranded conductors twisted together.

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* The wires in a stranded conductor are usually twisted or braided together.

† The first kind of cable is a single conductor, while the second kind is a roup of several conductors. The component conductors of the second kind f cable may be either solid or stranded, and this kind of cable may or may ot have a common insulating covering. The term "cable" is applied by me manufacturers to a solid wire heavily insulated and lead-covered; this sage arises from the manner of the insulation, but such a conductor is not cluded under this definition of "cable." The term "cable" is a general ne, and in practice, it is usually applied only to the larger sizes. A small able is called a "stranded wire" or a "cord," both of which are defined elow. Cables may be bare or insulated, and the latter may be armored ith lead, or with steel wires or bands.

‡ A wire has been defined as a slender rod or filament of drawn metal. f such a filament is subdivided into several smaller filaments or strands, nd is used as a single wire, it is called a "stranded wire." There is no harp dividing line of size between a "stranded wire" and a "cable." If sed as a wire, for example in winding inductance coils or magnets, it is alled a stranded wire and not a cable. If it is substantially insulated, it called a "cord," defined below.

§ There is no sharp dividing line in respect to size between a "cord" and "cable," and likewise no sharp dividing line in respect to the character f insulation between a "cord" and a "stranded wire." Rubber is used as he insulating material for many classes of cords.

‖ This kind of cable differs from the preceding in that the main strands re themselves stranded.

¶ It is not intended that the name as here given be actually used. One ould instead speak of a "3-conductor cable," a "12-conductor cable," etc. n referring to the general case, one may speak of a "multiple-conductor able" (as in Par. **9004** above).

** This kind of cable usually has only two or three conductors. Such ables are used particularly for alternating currents. The remark on the xpression "N-conductor" given for the preceding definition also applies ere.

†† They may or may not have a common insulating covering.

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9013. Twin cable. A twin cable is a cable composed of two insulated stranded conductors laid parallel, having a common covering.

9014. Twin wire. A twin wire is a cable composed of two small insulated conductors laid parallel, having a common covering.

*9015. **Triplex cable.** A triplex cable is a cable composed of three insulated single-conductor cables twisted together.

†9016. **Twisted pair.** A twisted pair is a cable composed of two small insulated conductors, twisted together, without a common covering.

‡9017. **Sector cable.** A sector cable is a multiple-conductor cable in which the cross-section of each conductor is substantially a sector, an ellipse, or a figure intermediate between them.

9018. Round conductor. A round conductor is either a solid or stranded conductor of which the cross-section is substantially circular.

§9019. **Split conductor.** A split conductor is a conductor which is divided into two or more parts, separated from one another by insulation which is thin compared with the insulation around the conductor.

9030. Factor of assurance. The factor of assurance of wire or cable insulation is the ratio of the voltage at which it is tested to that at which it is used.

9031. Insulation resistance. The insulation resistance of an insulated conductor is the electrical resistance offered by its insulation, to an impressed voltage tending to produce a leakage of current through the same.

‖**9032. Circular mil.** A circular mil is a unit of area equal to

$$\frac{\pi}{4} (= 0.7854\ldots) \text{ of a square mil.}$$

The cross-sectional area of a circle in circular mils is therefore equal to the square of its diameter in mils. A circular inch is equal to a million circular mils.

¶9033. **Lay.** The lay of any helical element of a cable is the axial length of a turn of the helix of that element.

9034. Direction of lay. The direction of lay is the lateral direction in which the strands of a cable run over the top of the cable as they recede from an observer looking along the axis of the cable.

ANNEALED COPPER STANDARD

9050. **Standard annealed copper. (*a*) *General:* The following shall be taken as normal values for standard annealed copper.

(*b*) *Resistance:* At a temperature of 20 deg. cent., the resistance of a wire of standard annealed copper one meter in length and of a uniform section of 1 sq. mm. is 1/58 ohm = 0.017241....ohm.

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* They may or may not have a common insulating covering.

† The two conductors of a "twisted pair" are usually substantially insulated, so that the combination is a special case of a "cord."

‡ Sector cables are used in order to obtain decreased overall diameter and thus permit the use of larger conductors in a cable of given diameter.

§ The term split conductor usually designates a conductor in two parts or splits, which may be either concentric or external to one another.

‖ A mil is the one-thousandth part of an inch. There are 1974 circular mils in a square millimeter.

¶ Among the helical elements of a cable may be each strand in a concentric-lay cable, or each insulated conductor in a multiple conductor cable.

** See I. E. C. Publication No. 28, "International Standard of Resistance for Copper," March, 1914.

Paragraphs (*b*) and (*c*) define what are sometimes called "Volume Resistivity" and "Mass Resistivity" respectively. This may be expressed in other units as follows:

Volume resistivity = 1.7241 microhms-cm. (microhms in a centimeter cube) at 20 deg. cent.

Mass resistivity = 875.20 ohms (mile, pound) at 20 deg. cent.

For detailed specifications of commercial copper see the Standard Specifications of the American Society for Testing Materials.

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(c) *Density:* At a temperature of 20 deg. cent., the density of standard nealed copper is 8.89 grams per cubic centimeter.
(d) *Temperature coefficient of resistance:* At a temperature of 20 deg. cent., e "constant mass" temperature coefficient of resistance of standard nealed copper, measured between two potential points rigidly fixed to e wire, is 0.00393 = $\frac{1}{254.45}$.... per deg. cent.
(e) *Resistance of standard annealed copper at 20 deg. cent.:* As a consequence, it follows from (a) and (b) that, at a temperature of 20 deg. cent. e resistance of a wire of standard annealed copper of uniform section, one eter in length and weighing one gram, is ($\frac{1}{8.89}$) × 8.89 = 0.15328.... ohm.

OPERATION

Temperature Limits

***9100. Maximum temperatures.** The temperature of the insulation a wire or cable at the surface of the conductor shall not be allowed to ceed the following values.

Let t = maximum safe temperature
E = r.m.s. operating electromotive force in kilovolts between conductors

Impregnated paper, $t = 85 - E$
Varnished cambric, $t = 75 - E$
Rubber insulation, $t = 60 - \frac{E}{4}$

DESIGNATION

9200. Designation of wires by diameter or gage number. The sizes wires shall be stated by their diameters in mils, the American Wire Gage Brown and Sharpe) sizes being taken as standard. For brevity, in cases here the most careful specification is not required, the sizes of wires may e stated by the gage number in the American Wire Gage.

9201. Designation of cables by cross-sectional area. The sizes of randed conductors shall be stated by their cross-sectional area in circular ils or circular inches, except in the case of flexible stranded conductors, or which see Par. **9402**. The cross-sectional aera of a cable shall be condered to be the sum of the cross-sectional areas of its component wires, hen measured perpendicular to their axes. The sizes of stranded conductors smaller than 250,000 circular mils (*i.e.*, No. 0000 A.W.G. or smaller) ay be stated by means of the gage number of a solid wire having the same ross-sectional area.

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* For example: At a working pressure of 3.3 kv., the maximum safe miting temperature at the surface of the conductor, or conductors, in a able would be as follows:

For impregnated paper	81.7 deg. cent.
For varnished cambric	71.7 deg. cent.
For rubber insulation	59.2 deg. cent.

The life of the insulation of a cable depends in a great measure upon the ctual temperature attained by the insulation. The result of operating at emperatures in excess of the safe limit is to shorten the life of the insulating naterial. When the safe limits are exceeded, deterioration is rapid and ermanent, the damage increasing with the length of time that the excessive emperature is maintained and with the amount of excess temperature until inally the insulation breaks down.

Some of the older types of cable for voltages above 7,500 have a dielectric oss that is so high that it may add considerably to the heating that would otherwise result. In such cases the dielectric loss is a material factor in letermining the safe load to be carried by the cable, and the safe operating emperature will be determined by the temperature at which cumulative eating occurs under the conditions of service, if this occurs at a lower temperature than that at which the insulation deteriorates.

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*9202. **Conductivity.** The conductivity of the metal of wires shall be expressed in terms of the conductivity of the Annealed Copper Standard as defined in Par. 9050.

†9203. **Copper-wire tables.** The copper-wire tables published by the Bureau of Standards in Circular No. 31 are adopted. Table VI therein gives the values of diameters and cross-sections of A. W. G. sizes to four significant figures. These Tables are based upon the Annealed Copper Standard described in Par. 9050.

TESTS

General

9300. **Cable lengths tested.** Electrical tests of insulation on wires and cables shall be made on the entire lengths to be shipped.

9301. **Immersion in water.** (*a*) *General:* The outer surface of the insulation of complete insulated wires and cables shall be grounded while being electrically tested. If the insulation is not provided with a conducting covering, and if the covering is not liable to injury by water, the ground shall be obtained by immersing the insulated wire or cable in water for at least twelve hours and testing at the end of that period while immersed. If the outer covering is susceptible to injury by immersion, the insulated conductor shall be tested before the application of such covering.

Dry core paper insulated lead covered cables, such as telephone and telegraph cables, for use in water, shall be tested after at least twelve hours immersion.

(*b*) *Multiple-conductor cable:* In the case of multiple-conductor cables without waterproof overall jacket of insulation, no immersion test should be made on finished cables, but only on the individual conductors before assembling.

Tests of Dielectric Strength

9310. **Object of Tests.** High-voltage tests are intended to detect weak spots in the insulation and to determine whether its dielectric strength is sufficient for enabling it to withstand the voltage to which it is likely to be subjected in service, with a suitable factor of assurance.

9311. **Nature of tests.** High-voltage tests shall be made at the factory by applying an alternating voltage between the conductor and sheath or water. The initially applied voltage must not be greater than the working voltage, and the rate of increase shall be approximately uniform and not over 100 per cent. in 10 sec.

‡9312. **Magnitude and duration of the test voltage.** (*a*) *General:* Wires and cables shall be tested at the place of manufacture for five consecutive minutes, except as provided in Par. 9312 (*b*) and (*f*).

(*b*) *Rubber insulation, National Electrical Code:* Rubber covered wires and cables for working pressures up to 600 volts alternating, insulated in accordance with the requirements of the National Electrical Code, shall be tested in accordance with that Code.

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* For any given wire, let
C = conductivity, in per cent. of Annealed Copper Standard
L = length, meters
R = resistance, ohms
W = weight, grams
t = temperature, deg. cent.
Then the conductivity may be derived from the following formula:

$$C = \frac{15.328}{\frac{WR}{L^2} + 0.000597(20 - t)}$$

† For detailed specifications of commercial copper, see the Standard Specifications of the American Society for Testing Materials.

‡ Hevea rubber is rubber from the Hevea Brasiliensis tree. Compounds containing 30 to 40 per cent. of Hevea rubber have electrical and mechanical properties superior to compounds insulated in accordance with the requirements of the National Electric Code.

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(c) *Thirty to forty per cent. Hevea rubber insulation for pressures up to* 600 *olts, alternating-current:* Wires and cables for working pressures up to 600 olts alternating, insulated with 30 to 40 per cent. Hevea rubber compound, nless the insulation thickness is less than specified in Par. **9405**, shall be sted in accordance with Table **901**.

Table 901. High-voltage tests for rubber-insulated wires and cables

(30 to 40 per cent. Hevea rubber insulation for working pressures up to 600 volts alternating-current)

Size A. W. G. or cir. mils	Size sq. mm.	Test pressure kilovolts
14–8	2.081– 8.366	3.0
7–0000	10.55 –107.2	3.5
250,000 and larger	127 and larger	4.0

(d) *Thirty to forty per cent. Hevea rubber insulation for pressures over* 600 *olts alternating-current:* Wires and cables insulated with 30 per cent. Hevea ubber compound for working pressures over 600 volts alternating, shall be ested with one kilovolt per 64th in. of thickness (2.53 kv. per mm.) up to $9\frac{4}{64}$ths in. (3.96 mm.). Above $1\frac{9}{64}$ths in. (3.96 mm.), the test pressure shall e 10 kv. plus 1.5 kv. per 64th in. (3.79 kv. per mm.) additional up to $3\frac{9}{64}$ths n. (11.89 mm.). Where the insulation thickness is $1\frac{9}{64}$ths in. (6.34 mm.) or ver, this rule shall apply only to conductors over 26,000 cir. mils (13.2 sq. mm.) area.

†(e) *Varnished cambric and impregnated paper insulation:* Varnished cambric and impregnated paper insulated wires or cables shall be tested in accordance with Table **902**.

Table 902. High-voltage tests for varnished cambric or impregnated paper insulated cables

(Minimum Values)

Operating kv.	Test kv.	Operating kv.	Test kv.
Below 0.5	2.5*	5.0	14.0
0.5	3.0	7.5	19.5
1.0	4.0	10.0	25.0
2.0	6.5	over 10	2½ times operating pressure
3.0	9.0		
4.0	11.5		

* The minimum thickness of insulation shall be $\frac{1}{16}$ in. (1.6 mm.)

For intermediate working voltages, the test voltage shall be interpolated.

(f) *Telephone, telegraph and annunciator wires and cables:* Section **9312** hall not apply to wires and cables for telephone, telegraph, annunciator and imilar devices.

9313. Frequency of test voltage. The frequency of the test voltage hall not exceed 100 cycles per second, and should approximate as closely as ossible to a sine wave. The source of energy should be of ample capacity.

9314. Dielectric strength tests. Ultimate dielectric strength tests, when required, shall be made on samples not more than 6 meters (20 ft.) ong. The maximum allowable temperature, at which the test is made, for he particular type of insulation and the particular working pressure, shall e not greater than the temperature limits given in Par. **9100**.

† Different engineers specify different thickness of insulation for the same working voltages. Therefore, at the present time the test kilovolt corresponding to working kilovolt given in Table **902**, are based on the *minimum* thickness of insulation specified by engineers and operating companies.

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9315. Multiple-conductor cables. If a multiple conductor cable is designed for the same operating voltage between conductors and sheath or water as between conductors, each conductor shall be tested against the other conductors connected together and to the sheath or water. If the cable is designed for an operating voltage between conductors and ground different from that between conductors, the test between conductors and the sheath or water shall be made separately and shall be based on the normal operating voltage between conductors and sheath or water as prescribed in Par. **9312.**

Insulation Resistance

*__9320. Expression of insulation resistance.__ Insulation resistance shall be expressed in megohms. Linear insulation resistance, or the insulation resistance of unit length, shall be expressed in terms of the megohm-kilometer, or the megohm-mile, or the megohm-thousand-feet, and shall be corrected to a temperature of 15.5 deg. cent., using a temperature coefficient determined experimentally for the insulation under consideration.

9321. Megohms constant. The megohms constant of an insulated conductor shall be the factor "K" in the following equation:

$$R = K \log_{10} \frac{D}{d}$$

where R = insulation resistance, in megohms, for a specified unit length.
D = outside diameter of insulation.
d = diameter of conductor.

Unless otherwise stated, K will be assumed to correspond to the mile unit of length.

9322. Measurement of insulation resistance. The apparent insulation resistance should be measured after the high-voltage test, measuring the leakage current after a one-minute electrification, with a continuous e.m.f. of from 100 to 500 volts, the conductor being maintained negative to the sheath or water.

9323. Insulation resistance of multiple-conductor cables. The insulation resistance of each conductor of a multiple-conductor cable shall be the insulation resistance measured from each conductor to all the other conductors in multiple with the sheath or water.

Capacitance or Electrostatic Capacity

†**9330. Expression of capacitance.** Capacitance shall be expressed in microfarads. Linear capacitance, or the capacitance of unit length, shall be expressed in microfarads per unit length (kilometer, or mile, or one thousand feet), and shall be corrected to a temperature of 15.5 deg. cent., using a temperature coefficient determined experimentally for the insulation under consideration.

9331. Microfarads constant. The microfarads constant of an insulated conductor shall be the factor "K" in the following equation:

$$C = \frac{K}{\text{Log}_{10} \frac{D}{d}}$$

where C = capacitance in microfarads per unit length.
D = outside diameter of insulation.
d = diameter of conductor.

Unless otherwise stated, K will be assumed to refer to the mile unit of length.

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* In the case of dry core paper insulated cables, the temperature coefficient of insulation resistance cannot be closely determined on account of variations in design and manufacture. Therefore no temperature corrections shall be applied to insulation resistance tests. Tests should be made at a temperature of 15.5 deg. cent. or higher.

† In the case of dry core paper insulated cables, the temperature coefficient of capacitance cannot be determined closely on account of variations in design and manufacture. Therefore no temperature corrections shall be applied to capacitance tests. Tests should be made at a temperature of 15.5 deg. cent. or higher.

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Table 903. Proposed standard cables

(This table is offered for consideration but will not be recommended fo nal adoption until ratified by other societies interested.)

Number and size. See Note 4	Strands		Total nominal cross-section circular mils	Total diameter inches
	Individual wires			
	Nominal diameter mils	Nominal circular mils		
127 No. 8	128.5	16,510.0	2,097,000	1.671
127 No. 9	114.4	13,090.0	1,662,000	1.487
91 No. 8	128.5	16,510.0	1,502,000	1.414
91 No. 9	114.4	13,090.0	1,191,000	1.258
61 No. 8	128.5	16,510.0	1,007,000	1.157
61-121 mils	121.0	14,641.0	893,100	1.089
61 No. 9	114.4	13,090.0	798,500	1.030
61-107 mils	107.0	11,449.0	698,400	0.963
61 No. 10	101.9	10,380.0	633,200	0.917
37-116 m ls	116.0	13,456.0	497,900	0.812
37 No. 10	101.9	10,380.0	384,100	0.713
37-97 mils	97.0	9,409.0	348,100	0.679
37 No. 11	90.74	8,234.0	304,700	0.635
19 No. 9	114.4	13,090.0	248,700	0.572
19-107 mils	107.0	11,449.0	217,500	0.535
19 No. 11	90.74	8,234.0	156,400	0.454
19 No. 12	80.81	6,530.0	124,100	0.404
19 No. 13	71.96	5,178.0	98,380	0.360
19 No. 14	64.08	4,107.0	78,030	0.320
7 No. 10	101.9	10,380.0	72,660	0.306
7 No. 11	90.74	8,234.0	57,640	0.272
7 No. 12	80.81	6,530.0	45,710	0.242
7 No. 14	64.08	4,107.0	28,750	0.192
7 No. 16	50.82	2,583.0	18,080	0.152
7 No. 18	40.30	1,624.0	11,370	0.121
7 No. 20	31.96	1,022.0	7,154	0.096
7 No. 22	25.35	642.4	4,497	0.076
7 No. 24	20.10	404.0	2,828	0.060

NOTE 1.—Nominal diameters and circular mils of the individual wires ar aken from Table VI, circular No. 31 of the Bureau of Standards.

NOTE 2.—The variation of the mean diameter of any wires shall not ex ed 1 per cent. above or below the nominal diameter.

NOTE 3.—The variation of the total cross-section of the cable shall no ceed 1 per cent. above or below the nominal cross-section.

NOTE 4.—Sizes are expressed as A.W.G. numbers except where diameter e given in mils.

9332. Measurement of capacitance. The capacitance of cable sha s measured with alternating current by comparison with a standard con enser. It is preferable that the measurement be made either at a frequenc pproximating that of operation or at a frequency giving results approxi ating those corresponding to the operating frequency or frequencies.

9333. Capacitance of paired cables. The capacitance of paired cable all be measured between the two conductors of any pair, the other wire ing connected to the sheath or ground.

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9334. Capacitance of multiple-conductor cables (not paired). The capacitance of multiple conductor (not paired) cables shall be measured between conductors, and also between each conductor and the other conductors connected to the sheath or ground.

CONSTRUCTION

Stranding

***9400. Proposed standard cables.** Insulated cables not requiring special flexibility shall be made of the number and size strands specified in Table 903.

9401. Cables not requiring special flexibility. Cables not requiring special flexibility and not made in accordance with Par. 9400 shall be stranded in accordance with Table 904.

Table 904. Standard stranding of concentric-lay cables

Size (see Note 1)	Square millimeters	Number of wires (see Note 2)	
		A Bare, insulated or weatherproof cables for aerial use	B Insulated cables for other than aerial use
2.0 cir. in.	1,013.0	91	127
1.5 cir. in.	760.0	61	91
1.0 cir. in.	507.0	61	61
0.6 cir. in.	304.0	37	61
0.5 cir. in.	253.0	37	37
0.4 cir. in.	203.0	19	37
0000 A.W.G.	107.0	19 or 7 (see Note 3)	19
00 A.W.G.	67.4	7	19
2 A.W.G.	33.6	7	7
7 and smaller	10.5	.....	7

NOTE 1.—For intermediate sizes, use stranding for next larger size.

NOTE 2.—Conductors of 0000 A.W.G. and smaller are often made solid and this table of stranding should not be interpreted as excluding this practice.

NOTE 3.—Class A cable, sizes 0000 and 000 A.W.G., is usually made of 7 strands when bare and 19 strands when insulated or weatherproof.

†**9402. Flexible cables.** Conductors of special flexibility should ordinarily be made with wires of regular A.W.G. sizes, and rated by the number and size of wires. The stranding of flexible cables is given in Table 906.

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* The basis of this rule is the use of strands of American Wire Gage sizes. To meet existing operating conditions, four sizes of strands other than American Wire Gage sizes have been deemed necessary and their diameters are shown in mils.

† Where necessary to closely approximate a regular size cable, the strands may be made of half-size wires from No. 15 to No. 30 A.W.G.

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Table 906. Stranding of flexible cables

Nearest A.W.G. size (see Note 1)	Circular mils (see Note 2)	Diam. of cable, mils	No. of wires	Size of each wire		Construction (see Note 3)
				A.W.G.	Diam. mils	
.....	2,039,000	1,885	703	15.5	53.9	37×19
.....	1,816,000	1,779	703	16.0	50.8	37×19
.....	1,617,000	1,679	703	16.5	48.0	37×19
.....	1,440,000	1,584	703	17.0	45.3	37×19
.....	1,284,000	1,496	703	17.5	42.7	37×19
.....	1,103,000	1,372	427	16.0	50.8	61×7
.....	874,600	1,222	427	17.0	45.3	61×7
.....	693,600	1,088	427	18.0	40.3	61×7
.....	550,000	969	427	19.0	35.9	61×7
.....	436,200	863	427	20.0	32.0	61×7
.....	345,900	768	427	21.0	28.5	61×7
.....	274,300	684	427	22.0	25.3	61×7
.....	264,600	671	259	20.0	32.0	37×7
0000	209,800	598	259	21.0	28.5	37×7
000	171,300	538	133	19.0	35.9	19×7
00	135,900	479	133	20.0	32.0	19×7
0	107,700	427	133	21.0	28.5	19×7
1	82,780	332	91	20.5	30.2	Concentric
2	65,650	295	91	21.5	26.9	Concentric
3	52,060	263	91	22.5	23.9	Concentric
4	39,190	228	61	22.0	25.3	Concentric
5	31,080	203	61	23.0	22.6	Concentric
6	24,650	181	61	24.0	20.1	Concentric
8	17,410	152	61	25.5	16.9	Concentric
10	10,560	118	37	25.5	16.9	Concentric
12	6,640	94	37	27.5	13.4	Concentric
14	4,176	74	37	29.5	10.6	Concentric
Smaller	.....	.....	To equal required size	30.0	....	Bunched

NOTE 1.—The A.W.G. cross-sectional areas except for 61 strands, ar approximated within 2 per cent. In the case of 61 strand cables the approxi mation is 6 per cent.

NOTE 2.—Circular mils are based on theoretical diameters of A.W.G sizes, which vary above or below values given in table by less than 0.1 mil

NOTE 3.—"61×7" in the rating of a rope-lay cable signifies 61 strand of 7 wires each.

***9403. Correction for lay.** Two per cent. shall be taken as the standar increment of resistance and of mass, due to stranding. In cases where th lay is definitely known, the increment should be calculated and not assumed

Thickness of Insulation

9406. Thickness of insulation for rubber insulated wires and cables Unless special conditions warrant departures from this rule, the thickne

* The resistance and mass of a stranded conductor are greater than in solid conductor of the same cross-sectional area, depending on the lay (*i.e.* the pitch of the twist of the wires).

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of insulation for rubber compounds containing from 30 to 40 per cent of Hevea rubber, shall be in accordance with Table 906.

Table 906. Thickness of insulation
30 to 40 per cent. heves rubber compound
Recommended Walls of Insulation, 64ths. Inch

Size A.W.G. or cir. mils	Square millimeters	Working pressure, volts alternating										
		600 or less	1500	2500	3500	5000	6000	7000	8000	9000	10000	11000
14-8	2.08-8.37	3	6	8	10	12	14	16	18	20	22	24
7-2	10.6-33.6	4	7	9	10	12	14	16	18	20	22	24
1-0000	42.4-107	5	8	10	10	12	14	16	18	20	22	24
250,000-500,000	127-253	6	9	10	11	12	14	16	18	20	22	24
550,000-1,000,000	279-507	7	10	10	12	12	14	16	18	20	22	24
1,250,000-2,000,000	633-1013	8	10	10	12	14	16	18	18	20	22	24

NOTES.—In multiple conductor cables, the thickness of insulation on each conductor shall be based on the highest r. m. s. voltage between the conductor and the outside of this insulation. The above table is based upon alternating voltages of commercial frequencies. For voltages over 600, the insulation thickness for direct-current cable has not been established. For intermediate sizes the insulation thickness should be the same as for the next larger sizes.

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CHAPTER X

STANDARDS FOR STORAGE BATTERIES

Rules to be included in the Chapter have been prepared, and await final consideration before publication.

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CHAPTER XI

STANDARDS FOR ILLUMINATION

This chapter consists of extracts from the Report of the Committee on omenclature and Standards of the Illuminating Engineering Society for e year 1918. It is here included by permission.

General

11000. Radiant flux, ϕ, is the rate of flow of radiation evaluated with ference to energy, and is expressed in ergs per second or in watts.

11001. Luminous flux, F, is the rate of flow of radiation evaluated with ference to visual sensation, and is expressed in lumens.

11002. Visibility, K_λ, of radiation of a particular wave-length is the ratio the luminous flux at that wave-length to the corresponding radiant flux. Defining equation:

$$K_\lambda = \frac{F_\lambda}{\Phi_\lambda}$$

***11003. The mechanical equivalent of light** is the ratio of radiant ux to luminous flux for the wave-length of maximum visibility, and is pressed in ergs per second per lumen, or in watts per lumen. It is the ciprocal of the maximum visibility.

11004. Luminosity of a particular wave-length is the product of the sibility of that wave-length and the corresponding ordinate of the spectral rve of radiant flux, and is represented by the ordinate of the spectral curve luminous flux. This curve is called the spectral luminosity curve and different with different sources.

11005. The luminous efficiency of any source is the ratio of the lumi- ous flux to the radiant flux from the source and is expressed in lumens per att.

11006. Luminous intensity I, of a source of light in a given direction the solid angular density of the luminous flux emitted by the source in e direction considered, when the flux involved acts as far as computation nd measurements are concerned, as if it came from a point. Or, it is the ux per unit solid angle from that source in the direction considered. The ux from any source of dimensions which are negligibly small by comparison ith the distance at which it is observed, may be treated as if it were emitted om a point.

Defining equation:

$$I = \frac{dF}{d\omega}$$

r, if the intensity is uniform,

$$I = \frac{F}{\omega}$$

here ω is the solid angle.

11007. Illumination, E, of a surface at any point is the luminous flux ensity on the surface at that point, or the flux per unit of intercepting area. Defining equation:

$$E = \frac{dF}{dS}$$

r, when uniform,

$$E = \frac{F}{S}$$

here S is the area of the intercepting surface.

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* This term has been used in a variety of senses. As here defined it refers nly to the minimum mechanical equivalent of light. The reciprocal of his quantity is sometimes called the luminous equivalent of radiation.

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*11008. **Candle** is the unit of luminous intensity maintained by the national laboratories of France, Great Britain, and the United States.

11009. **Candlepower,** cp., is luminous intensity expressed in candles.

† 11010. **Lumen,** *l.*, is the unit of luminous flux equal to the flux emitted in a unit solid angle (steradian) by a point source of unit candlepower.

11011. **Lux** is a unit of illumination equal to one lumen per sq. m. Using the centimeter as the unit of length, the unit of illumination is one lumen per sq. cm., for which Blondel has proposed the name **phot.** One millilumen per sq. cm. (**milliphot**) is more useful as a practical unit. (By) **foot-candle** is one lumen per sq. ft., and is equal to 1.0764 milliphots. The milliphot is recommended for scientific records.

11012. **Brightness** of an element of a luminous surface may be expressed in either of two ways: (*a*) in terms of intensity, *I*, (*b*) in terms of flux, *F*.

(*a*) Brightness in terms of the luminous intensity *I* (or candle-power) per unit of projected area of the surface (candlepower brightness) corresponds to the

$$\text{defining equation, } b_I = \frac{dI}{dS \cos \theta}$$

where θ is the angle between the normal to the surface and the line of sight.

(*b*) Brightness in terms of the flux, *F*, proceeding from a unit area of the surface, on the assumption that the surface is a perfect diffuser; i.e., that it obeys the cosine law of emission or reflection, (lumen brightness) corresponds to the

$$\text{defining equation, } b_F = \frac{dF}{dS}$$

(perfect diffusion assumed).

The units in which brightness is measured according to (*a*) and (*b*) differ only in numerical value.

11013. **Lambert,** *L*, is the unit of brightness in the lumen system. The lambert is the brightness of a perfectly diffusing surface emitting or reflecting one lumen per sq. cm. For most purposes the **millilambert,** 0.001 lambert, is the preferable practical unit.

To say that the brightness of a surface as viewed from a given point is *n* lamberts, signifies that its brightness is the same as that of a perfectly diffusing surface emitting or reflecting *n* lumens per sq. cm.

In practice no surface obeys exactly the cosine law of emission or reflection; hence the brightness of a surface generally is not uniform but varies somewhat with the angle at which it is viewed.

A perfectly diffusing surface emitting one lumen per sq. ft. will have a brightness of 1.076 millilamberts.

Brightness expressed in candles per sq. cm. may be reduced to lamberts by multiplying by $\pi = 3.14$.

Brightness expressed in candles per sq. in. may be reduced to lamberts by multiplying by $\pi/6.45 = 0.487$.

Surfaces and Media Modifying Luminous Flux

11020. **Diffusing** surfaces and media are those which break up the incident flux and distribute it more or less in accordance with the cosine law, as for example, white plaster and opal glass.

11021. **Redirecting** surfaces and media are those which change the direction of the luminous flux in a definite manner; as for example, a mirror or a lens.

11022. **Scattering** surfaces and media are those which redirect the luminous flux and break it up into a multiplicity of separate pencils; as for example, ripple glass, reflecting or transmitting.

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* This unit, which is used also by many other countries, has frequently been referred to as the international candle.

† A uniform source of one candlepower emits 4π lumens.

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*11023. **Reflection factor**, of a body ρ, is the ratio of the flux reflected
r the body to the flux incident upon it. The reflection from a body may
regular, diffuse or mixed. In regular reflection the flux is reflected at an
ngle of reflection equal to the angle of incidence. In diffuse reflection the
ux is reflected in all directions. In perfectly diffuse reflection, the distri-
ution of the reflected flux is in accordance with Lambert's cosine law. In
ost practical cases, there is a superposition of regular and diffuse reflection.

*11024. **Absorption factor**, of a body a, is the ratio of the flux absorbed
r the body to the flux incident upon it.

*11025. **Transmission factor**, of a body τ, is the ratio of the flux trans-
itted by the body to the flux incident upon it.

$$\rho + a + \tau = 1$$

Illumination

11030. **Unidirectional** illumination on a surface is that produced by a
ngle light source of relatively small dimensions. It is characterised by
e fact that a small opaque object placed near the illuminated surface casts
sharp shadow.

11031. **Multidirectional** illumination on a surface is that produced by
veral separated light sources of relatively small area. It is characterized
r the fact that a small opaque object placed near the illuminated surface
sts several shadows.

11032. **Diffused** illumination is that produced either by primary or sec-
ndary light sources having dimensions relatively large with respect to the
stance from the point illuminated, and scattering light in all directions.
is characterised by relative lack of shadow. Diffused illumination may
derived principally from a single direction as in the light from a skylit
indow or from all directions as in the open air. Perfectly diffused illumina-
on on a surface is shadowless.

In any practical case of illumination on a surface there is usually a mixture
the above types.

11033. **Coefficient of utilization** of an illumination installation on a
ven plane is the total flux received by that plane divided by the total flux
om the lamps illuminating it. When not otherwise specified, the plane
reference is assumed to be a horizontal plane 30 inches (76 cm.) from
ie floor.

11034. **Variation factor** of an illumination installation is the ratio of
ther the maximum or minimum illumination on a given plane to the aver-
ge illumination on that plane.

11035. **Variation range** of illumination on a given plane is the ratio of
ie maximum illumination to the minimum illumination on that plane.

11036. **Hemispherical ratio** for a given lighting unit is the ratio of the
minous flux in the upper hemisphere to that in the lower hemisphere.

11037. **Brightness ratio** is the ratio of the brightness of any two sur-
ces. When the two surfaces are opposed, the brightness ratio is commonly
lled the "brightness contrast."

Illuminants

11040. The **output** of all illuminants should be expressed in lumens.

11041. **Illuminants should be rated** upon a lumen basis rather than a
ndlepower basis.

11042. **Lamp efficiency** is the ratio of the luminous flux output to the
ower input.

---

* These terms are introduced to replace the more commonly used terms,
efficient of reflection, coefficient of absorption, coefficient of transmission.
hich latter terms refer to the specific properties of materials rather than
the behavior of bodies under specified conditions, such as angle of inci-
ence, etc.

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11043. The lamp efficiency or **specific output of electric lamps** should be stated in terms of lumens per watt and that of illuminants depending upon combustion should be stated in lumens per British thermal unit per hour.

11044. The power consumption of auxiliary devices which are necessarily employed in circuit with a lamp should be included in the input of the lamp. For example, the watts lost in the ballast resistance of an arc lamp are properly chargeable to the lamp.

11045. The specific consumption of an electric lamp is its watt consumption per lumen. "Watts per candle" is a term used commercially in connection with electric incandescent lamps, and denotes watts per mean horisontal candle.

11046. Life tests. Electric incandescent lamps of a given type may be assumed to operate under comparable conditions only when their lumens per watt consumed are the same. Life test results, in order to be compared, must be either conducted under, or reduced to, comparable conditions of operation.

11047. In comparing different luminous sources not only should their candlepower be compared, but also their relative form, brightness, distribution of illumination and character of light.

Lamp Accessories

11048. A **reflector** is an appliance the chief use of which is to redirect the luminous flux of a lamp in a desired direction or directions.

11049. A **shade** is an appliance the chief use of which is to diminish or to interrupt the flux of a lamp in certain directions where such flux is not desirable. The function of a shade is commonly combined with that of a reflector.

11050. A **globe** is an enclosing appliance of clear or diffusing material the chief use of which is either to protect the lamp or to diffuse its light.

Photometry

11060. Performance curve is a curve representing the behavior of a lamp in any particular (candlepower, consumption, etc.) at different periods during its life.

11061. Characteristic curve is a curve expressing a relation between two variable properties of a luminous source, as candlepower and volts, candlepower and rate of fuel consumption, etc.

11062. Mean horizontal candlepower of a lamp is the average candlepower in the horisontal plane passing through the luminous center of the lamp.

It is here assumed that the lamp (or other light source) is mounted in the usual manner, or, as in the case of an incandescent lamp, with its axis of symmetry vertical.

11063. Mean spherical candlepower of a lamp is the average candlepower of a lamp in all directions in space. It is equal to the total luminous flux of the lamp in lumens divided by 4π.

11064. Mean hemispherical candlepower of a lamp (upper or lower) is the average candlepower of a lamp in the hemisphere considered. It is equal to the total luminous flux emitted by the lamp in that hemisphere divided by 2π.

11065. Mean zonal candlepower of a lamp is the average candlepower of a lamp over the given zone. It is equal to the total luminous flux emitted by the lamp in that zone divided by the solid angle of the zone.

***11066. Spherical reduction factor** of a lamp is the ratio of the mean spherical to the mean horisontal candlepower of the lamp.

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* In the case of a uniform point-source, this factor would be unity, and for a straight cylindrical filament obeying the cosine law it would be $\pi/4$.

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Table 1100

11067. Photometric units and abbreviations

Photometric quantity	Name of unit	Symbols and defining equations	Abbreviation for name of unit
1. Luminous flux	Lumen	F, ψ	l.
2. Luminous intensity	Candle	$I = \frac{dF}{d\omega}$, $\Gamma = \frac{d\psi}{d\omega}$	cp.
3. Illumination	Phot, foot-candle, lux	$E = \frac{dF}{dS} = \frac{I}{r^2} \cos \theta$.	ph. fc.
4. Exposure	Phot-second	Et	phs.
	Micro phot-second		μ phs.
5. Brightness	Apparent candle per sq. cm.		
	Apparent candle per sq. in.	$b_d = \frac{dI}{dS \cos \theta}$	
	Lambert	$b_l = \frac{dF}{dS}$	L. mL.
6. Reflection factor...		ρ	
7. Absorption factor.		α	
8. Transmission factor			τ
9. Mean spherical candlepower			scp.
0. Mean lower hemispherical candlepower			lcp.
. Mean upper hemispherical candlepower			ucp.
. Mean zonal candlepower			zcp.
. Mean horizontal candlepower			mhc.

. 1 lumen is emitted by 0.07958 spherical candlepower.
. 1 spherical candlepower emits 12.57 lumens.
. 1 lux = 1 lumen incident per square meter = 0.0001 phot = 0.1 milliphot.
. 1 phot = 1 lumen incident per sq. cm. = 10,000 lux = 1,000 milliphots = 1,000,000 microphots.
. 1 milliphot = 0.001 phot = 0.929 foot-candle.
. 1 foot-candle = 1 lumen incident per sq. ft. = 1.076 milliphots = 10.76 lux.
. 1 lambert = 1 lumen emitted per sq. cm. of a perfectly diffusing surface.
. 1 millilambert = 0.001 lambert.
2. 1 lumen, emitted, per sq. ft. = 1.076 millilamberts.
3. 1 millilambert = 0.929 lumen, emitted, per sq. ft.
. 1 lambert = 0.3183 candle per sq. cm. = 2.054 candles per sq. in.
. 1 candle per sq. cm. = 3.1416 lamberts.
. 1 candle per sq. in. = 0.487 lambert = 487 millilamberts.

CHAPTER XII

STANDARDS FOR TELEPHONY AND TELEGRAPHY

Many of the following definitions are tentative and not yet fully established. Criticisms and suggestions, addressed to the Secretary of the Standards Committee, will be welcomed. Some of the definitions are specific to lephony, and differ in detail from similar definitions appearing in other rts of the rules.

DEFINITIONS

Line Circuits

12000. Ground-return circuit. A ground-return circuit is a circuit nsisting of one or more metallic conductors in parallel, with the circuit mpleted through the earth.

12001. Metallic circuit. A metallic circuit is a circuit of which the rth forms no part.

* Perfect diffusion assumed.

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12002. Two-wire circuit. A two-wire circuit is a metallic circuit formed by two parallel conductors insulated from each other.

12003. Superposed circuit. A superposed circuit is an additional circuit obtained from a circuit normally required for another service, and in such a manner that the two services can be given simultaneously without mutual interference.

12004. Phantom circuit. A phantom circuit is a superposed circuit each side of which consists of the two conductors of a two-wire circuit in parallel.

12005. Side circuit. A side circuit is a two-wire circuit forming one side of a phantom circuit.

12006. Non-phantomed circuit. A non-phantomed circuit is a two-wire circuit, which is not arranged for use as the side of a phantom circuit.

12007. Simplexed circuit. A simplexed circuit is a two-wire telephone circuit, arranged for the superposition of a single ground-return signaling circuit operating over the wires in parallel.

12008. Composited circuit. A composited circuit is a two-wire telephone circuit, arranged for the superposition on each of its component metallic conductors, of a single independent ground-return signaling circuit.

12009. Quadded or phantomed cable. A quadded or phantomed cable is a cable adapted for the use of phantom circuits.

12010. Simplex circuit. A simplex circuit in telegraphy is one arranged for operation in one direction at one time.

12011. Duplex circuit. A duplex circuit in telegraphy is one arranged for simultaneous operation in opposite directions.

12012. Diplex circuit. A diplex circuit in telegraphy is one arranged for the simultaneous transmission of two messages in the same direction.

12013. Quadruplex circuit. A quadruplex circuit in telegraphy is one arranged for the simultaneous transmission of two messages in each direction.

12014. Multiplex circuit. A multiplex circuit in telegraphy is one arranged for the simultaneous transmission of one or more messages in both directions. Both duplex and quadruplex are examples of multiplex whereas diplex is not.

12015. Linear electrical constants. The linear electrical constants of a line are the electrical constants per unit length of the line, *e.g.*, linear resistance, linear inductance, etc.

12016. Smooth line. A smooth line is a line whose electric elements are all continuously and uniformly distributed throughout its length.

*__12017. Periodic line.__ A periodic line is a line consisting of successive similar sections in each of which one or more electric elements are not distributed uniformly. As examples of periodic lines are (1) loaded lines and (2) artificial lines consisting of successive similar sections of lumped constants.

12018. Equivalent smooth line. An equivalent smooth line of a periodic line is a smooth line having the same electrical behavior as the periodic line, at a given single frequency, when measured at terminals or at corresponding section junctions.

12019. Equivalent periodic line. An equivalent periodic line of a smooth line is a periodic line having the same electrical behavior, for an assumed single frequency, as the smooth line, when measured at terminals or at corresponding section junctions. The terms conjugate smooth line and conjugate periodic line are also sometimes used.

12020. Composite line. A composite line is a line consisting of a plurality of successive sections having different linear electrical constants, as in the case where an underground cable section is joined to an overhead open-wire section.

12021. Loaded line. A loaded line is one in which the normal reactance of the circuit has been altered for the purpose of increasing its transmission efficiency.

* The term periodic in this definition refers to the line constants and not to time relations.

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. **Series loaded line.** A series loaded line is one in which the reactance has been altered by reactance serially applied.

. **Shunt loaded line.** A shunt loaded line is one in which the reactance of the circuit has been altered by reactance applied in roes the circuit.

. **Continuous loading.** A continuous loading is a series loading i the added inductance is uniformly distributed along the conductors.

5. Coil loading. A coil loading is one in which the normal induc- altered by the insertion of lumped inductance in the circuit at s.

Circuit Constants and Characteristics

). **Damping of a circuit.** The damping at a given point in a cir- m which the source of energy has been withdrawn, is the progressive ion in the effective value of electromotive force and current at that sulting from the withdrawal of electrical energy.

51. **Damping constant.** The damping constant of a circuit is a e of the ratio of the dissipative to the reactive component of its admit- r impedance.

52. **Mutual impedance.**—The mutual impedance for single fre- alternating currents, between a pair of terminals and a second pair ainals of a network, under any given condition, is the negative ratio electromotive force produced between either pair of terminals on ircuit to the current flowing between the other pair of terminals.

53. **Self-impedance.** The self-impedance between a pair of ter- of a network, under any given condition, is the ratio of the electro- force applied across the terminals to the entering current.

54. **Characteristic impedance.** The characteristic impedance of is the ratio of the applied electromotive force to the resulting steady- current upon a line of infinite length and uniform structure, or of ic recurrent structure.

055. **Sending-end impedance.** The sending-end impedance of a

---

is lumped inductance may be applied either in series or in shunt.
commonly understood, coil loading is a series loading, in which the d inductance is applied at uniformly spaced recurring intervals.
pplied to the admittance of a condenser or other simple circuit having ity reactance, the damping constant for a harmonic electromotive force en frequency is the ratio of the conductance G, of the condenser or e circuit at that frequency to twice the capacitance, C, of the condenser same frequency ($G/2C$).
plied to the reactance of a coil or other simple circuit having inductive ance, the damping constant for a harmonic current of a given frequency ratio of the resistance, R, of the coil or circuit at that frequency to the inductance, L, at the same frequency ($R/2L$).
receiving-end impedance is an example of a mutual impedance.
ngle frequency voltages and currents are here supposed to be represented omplex numbers. Their ratio is therefore a complex number.
ingle frequency voltages and currents are here supposed to be repre- d by complex numbers. Their ratio is therefore a complex number.
In practice, the terms (1) line impedance, (2) surge impedance, (3) itera- impedance, (4) sending-end impedance, (5) initial sending-end imped- , (6) final sending-end impedance, (7) natural impedance and (8) free dance, have apparently been more or less indefinitely and indiscrimi- ly used as synonyms with what is here defined as "characteristic im- ance."
ngle frequency voltages and currents are here supposed to be represented omplex numbers. Their ratio is therefore a complex number.
See note under "Characteristic Impedance." In case the line is of in- e length of uniform structure or of periodic recurrent structure, the send- end impedance and the characteristic impedance are the same.
ingle frequency voltages and currents are here supposed to be represented complex numbers. Their ratio is therefore a complex number.

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line is the ratio of the applied electromotive force to the resulting steady-state current at the point where the electromotive force is applied.

*12066. **Propagation constant.** The propagation constant of a uniform line, or section of a line of periodic recurrent structure, is the natural logarithm of the ratio of the steady-state currents at various points separated by unit length in a uniform line of infinite length, or at successive corresponding points in a line of recurrent structure of infinite length. The ratio is determined by dividing the value of the current at the point nearer the transmitting end by the value of the current at the point more remote.

12067. **Attenuation constant.** The attenuation constant for a single frequency is the real part of the propagation constant taken at that frequency.

12068. **Wave-length constant.** The wave-length constant is the imaginary part of the propagation constant.

12069. **Standard cable.** A standard cable is an ideal uniform line in terms of which the attenuation of a line or network may be specified. It is characterized by the following constants: Linear resistance, 88 ohms per loop mile (54.7 ohms per loop km.). Linear capacitance between wires 0.054 microfarad per loop mile (0.03355 microfarad per loop km.). Linear inductance and linear leakance, 0.

Equivalent Circuits

†12102. **Equivalent circuit.** An equivalent circuit is a simple network of series and shunt impedances, which, at a given frequency, is the approximate electrical equivalent of a complex network.

†12103. "*T*" **equivalent circuit.** A "*T*" equivalent circuit is a triple-star or "*Y*" connection of three impedances externally equivalent to a complex network. See Fig. 12-1 for symbol.

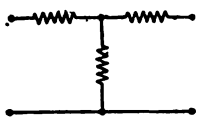


FIG. 12-1

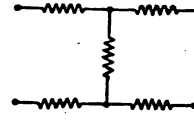


FIG. 12-2

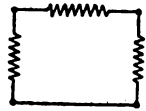


FIG. 12-3

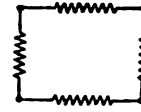


FIG. 12-4

†12104. "*I*" **equivalent circuit.** An "*I*" equivalent circuit is a connection of five impedances in the form shown in Fig. 12-2, which is externally equivalent to a complex network. It differs from the "*T*" equivalent circuit in that the impedances are arranged symmetrically on the two sides of the circuit, which is often desirable in connection with practical problems, as indicating that the circuit is balanced with respect to ground.

†12105. "**II**" **equivalent circuit.** A "**II**" equivalent circuit is a delta connection of three impedances externally equivalent to a complex network. It is also called a "*U*" equivalent circuit. See Fig. 12-3 for symbol.

†12106. "*O*" **equivalent circuit.** An "*O*" equivalent circuit is a connection of four impedances in the form shown in Fig. 12-4, externally equiva-

* Single frequency voltages and currents are here supposed to be represented by complex numbers. Their ratio is therefore a complex number.

† As ordinarily considered, the simple networks as defined, are the electrical equivalents of complex networks only with respect to definite pairs of terminals.

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complex network. It differs from the Π equivalent circuit in that
edances are arranged symmetrically on the two sides of the circuit,
often desirable in connection with practical problems, as indicating
circuit is balanced with respect to ground.

Telephony.

Manual telephone system. A manual telephone system is one
h the calling party gives his order to an operator who completes the
ectly by hand, either with or without the assistance of one or more
nal operators.

1. Automatic or full mechanical telephone system. An auto-
or full mechanical telephone system is one in which the calling party
led to complete a call by remote-control switches without the aid of
rator.

2. Semi-automatic or semi-mechanical telephone system. A
utomatic or semi-mechanical telephone system is one in which the
party gives his order to an operator who completes the call through
-control switches.

3. Telephone exchange. A telephone exchange consists of one or
central offices with associated plant, by means of which telephone
e is rendered in a specified local community.

04. Telephone exchange area or district. A telephone exchange
r district is the area or district served by a telephone exchange.

05. Central office. A central office is a switching center for inter-
cting lines terminating therein.

06. Toll central office. A toll central office is one in which toll and
distance lines terminate.

07. Local central office. A local central office is one in which sub-
er's lines terminate.

08. Private branch exchange (generally abbreviated "P. B. X.").
ivate branch exchange is a telephone system generally installed on the
ises of a subscriber, including a switchboard and extension sets, and
ected to a central office, affording intercommunication between the
asion sets and also between these sets and the central office.

09. Private exchange. A private exchange is one which serves one
ness organization or individual, and is not connected to a central office.

10. Private automatic exchange. A private automatic exchange
n automatic exchange which serves one business organization or indi-
ual, and is not connected to a central office.

11. Subscriber set (often abbreviated to "subset"). A sub-
ber set is an assembly of apparatus for sending and receiving telephone
s.

12. Subscriber station (often abbreviated to "substation"). A
scriber station is an installed subscriber set connected to a central office
the purpose of sending and receiving telephone calls.

13. Pay station. A pay station is a subscriber station available for
use of the public on the payment of a fee. The fee may be either de-
ited in a coin box or paid to an attendant.

14. Toll station. A toll station is a pay station located outside of
ocal service area and affording toll and long distance service only.

15. Subscriber line or subscriber loop. A subscriber line or sub-
iber loop is the wire connection between a subscriber station and the cen-
al office.

16. Subscriber line circuit. A subscriber line circuit is a sub-
riber line with its associated individual central office apparatus.

17. Individual line. An individual line is a subscriber line which
nnects one subscriber station to a central office, though it may have one
more extension sets.

18. Party line. A party line is a subscriber line which connects two
r more subscriber stations to a central office.

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12219. Tip side or tip wire, ring side or ring wire. The tip side or wire, or the ring side or wire, is that conductor of a circuit which is associated with the corresponding member of a jack.

12220. Negative side or negative wire, positive side or positive wire. The negative side or wire, or the positive side or wire, is that conductor of a circuit which is normally connected to the corresponding pole of a battery.

12221. Main distributing frame. A main distributing frame is a structure for terminating the permanent inside and outside wires of a central office and for effecting flexible junctions between them.

12222. Intermediate distributing frame. An intermediate distributing frame is a structure for terminating permanent inside wires of a central office and for effecting flexible junctions between them.

12223. Switchboard. A switchboard is an assemblage of apparatus in a coordinate structure for switching talking and signaling circuits.

12224. Switchboard section. A switchboard section is an element or unit one or more of which constitutes a complete manual switchboard.

12225. Operating room. An operating room is a room which contains a manual switchboard and associated apparatus.

12226. Combination current. A combination current consists of two or more currents of different characteristics in the same circuit. As ordinarily used the term refers to currents whose characteristics are steadily maintained, as for example, a combination of direct current and an alternating current.

12227. Manual ringing. Manual ringing is ringing which is affected by and continues with the operation of a key.

12228. Machine ringing. Machine ringing is intermittent and is caused to act periodically by the apparatus itself.

12229. Superimposed ringing current. A superimposed ringing current is a combination current for ringing, consisting of a direct and an alternating current.

12230. Pulsating ringing current. A pulsating ringing current is a current for ringing in which the succeeding impulses are separated by intervals approximately equal to those of the impulses themselves.

12231. Harmonic selective signaling. Harmonic selective signaling employs devices tuned mechanically or electrically to the frequency of the ringing current, so that each device will not operate when receiving current intended to operate another device.

12232. Multiple harmonic signaling. Multiple harmonic signaling employs frequencies which are integral multiples of the lowest frequency.

12233. Non-multiple harmonic signaling. Non-multiple harmonic signaling employs frequencies which are not integral multiples of the lowest frequency.

12234. "To call." "To call" is to originate a telephone call.

12235. "To dial." "To dial" a number is to use a dial type of calling device in order to control automatic switches.

12236. "To set up." "To set up" a number is to use a key type or multiple lever type of calling device in order to control automatic switches.

12237. Calling device. A calling device is an apparatus by means of which automatic switches are controlled for the purpose of establishing a connection.

12238. Calling party. A calling party is a person who originates a telephone call.

12239. Called party. A called party is the person who answers when a station is called.

12240. Reverting call. A reverting call is one between two stations on the same subscriber line.

12241. Telephone traffic. Telephone traffic is the aggregate volume of communication handled in a given time.

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12242. "Busy." "Busy" is the condition of a line or an apparatus when is in use.

12243. Free. Free is the condition of a line or an apparatus when it is t in use. Free is the opposite of busy.

12244. "To make busy." "To make busy" is to cause a line or an paratus to appear to be busy.

12245. "To release" or to "disconnect." "To release" or "to disnnect" is to terminate a telephone connection by disengaging the apparatus.

12246. "To clear." "To clear" is to restore a line or an apparatus to e free condition.

12247. Trunk. A trunk is the wire connection between switching devices central offices.

12248. Trunk circuit. A trunk circuit is a trunk with its associated dividual apparatus.

12249. Trunked call. A trunked call is one which employs an interfice trunk or a trunk between two switchboard positions.

12250. Relay. A relay is a device by means of which contacts in one rcuit are operated by a change in conditions in the same circuit or in one more associated circuits. (See Rule 4016 Standardization Rules, A. I. E. ., 1918).

12251. Polar relay. A polar relay is a relay which operates in response a change in the direction of the current in the controlling circuit.

12252. Quick operating relay. A quick operating relay is one which perates its contacts within a specified brief time limit.

12253. Quick release relay. A quick release relay is one which releases s contacts within a specified brief time limit.

12254. Quick acting relay. A quick acting relay is one which has the roperties of both a quick operating and a quick release relay.

12255. Slow operating relay. A slow operating relay is one which will ot operate until after a specified delay.

12256. Slow release relay. A slow release relay is one which when perated will not release until after a specified delay.

12257. Slow acting relay. A slow acting relay is one which has the roperties of both a slow operating and a slow release relay.

12258. Line relay. A line relay is one whose coil is normally in the line ircuit.

12259. Cut-off relay. A cut-off relay is one which when operated disonnects from a line apparatus normally connected to it.

12260. Relay coil section. A relay coil section is one of two or more indings of a coil on one and the same core. The several sections may be oncentric or placed side by side on the core.

12261. Tension spring. A tension spring is one which functions to xert mechanical pressure but does not carry an electrical current.

12262. Contact spring. A contact spring is one which takes an electrical part in switching a circuit.

12263. Main contact spring. A main contact spring is one which may switch a circuit between two or more other contact springs.

12264. Armature spring. An armature spring is the first of a group to be moved by the armature. It may or may not be a main contact spring.

12265. Plunger spring. A plunger spring is the first of a group to be moved by the plunger.

12266. Impulse springs. Impulse springs are those which act to make or break a circuit for the purpose of sending impulses.

12267. Make-before-break contact springs (abbreviation "M.B.B."). Make-before-break contact springs are those in which the main spring touches the front contact before it breaks away from the back contact. Also called a continuity preserving contact.

12268. Back contact spring. A back contact spring is one against which the main contact spring rests when in the normal position.

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12269. Front contact spring. A front contact spring is one against which the main contact spring rests when in the operated position.

12270. Automatic signaling. Automatic signaling is affected without the aid of an operator.

12271. Automatic switch. An automatic switch is a remote control device for controlling talking or signaling circuits.

12272. Finder switch. A finder switch is a switch connected to one of a smaller number of circuits and which finds automatically a circuit out of a larger number of circuits from whence the signal comes.

12273. Line switch. A line switch is a switch connected to one of a larger number of circuits from which a signal comes and which finds automatically a circuit out of a smaller number of circuits.

12274. Selector switch. A selector switch is a switch whose duty is to select a particular group of trunks and one trunk of the group selected. In particular cases, one of these functions may be omitted.

12275. Connector switch or final selector. A connector switch or final selector is a switch whose duty is to establish a connection with the called line. It is usually operated by the last digit or digits of the call number.

12276. Switch frame. A switch frame is a structure for mounting an assembly of switching apparatus which may be integral therewith.

12277. Section of switches. A section of switches, considered from a trunking standpoint, is a group of adjacent switches whose banks are multiplied together.

12278. Switchroom. A switchroom is a room which contains an assemblage of automatic switches and associated apparatus.

12279. Bank wires. Bank wires are those wires which multiple adjacent switch banks to each other.

12280. Bank cable. A bank cable is one which connects a switch bank to a terminal rack.

12281. Multiple cable. A multiple cable is one which multiplies together two or more sections of switch banks by connecting together their terminals.

12282. Impulse. An impulse is any sudden change of brief duration produced in the current of a circuit.

12283. Make impulse. A make impulse is an impulse due to a temporary flow of current.

12284. Break impulse. A break impulse is an impulse due to a temporary interruption of current.

12285. Impulse frequency. The impulse frequency is the number of impulses occurring per second. The reciprocal of this is the impulse period.

12286. Impulse period. The impulse period is the period of time included between the corresponding points in periodically recurring impulses. It thus corresponds to the period of alternating current.

12287. Impulse ratio. Impulse ratio is the ratio of duration of an impulse to the impulse period.

12288. Impulse circuit. An impulse circuit is one through which impulses are transmitted.

12289. Telephone impulse repeater. A telephone impulse repeater is a device for repeating impulses from one line circuit into another and for performing other duties.

12290. Supervisory signal. A supervisory signal is a device for attracting attention of an attendant to a duty in connection with switching apparatus or its accessories. This includes cord supervisory lamps on a manual switchboard and the supervisory lamps in an automatic exchange which indicates that a switch has been occupied but has not completed its function.

12291. Tell-tale signal. A tell-tale signal is a device for locating the failure of some apparatus; for example, the blowing of a fuse, the continued drawing of heavy current by apparatus intended to receive only momentary current, etc.

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2. Alarm signal. An alarm signal is a sound producing device for ing attention to either a supervisory or a tell-tale signal.

3. Amplifier. See Par. 13040.

4. Telephone repeater. A telephone repeater is a device for amg a voice current from one line circuit into another line circuit.

0. Telephone receiver. A telephone receiver is an electrically operevice designed to produce sound waves or vibrations which correspond electromagnetic waves or vibrations actuating it.

01. Microphone. A contact device designed to have its electrical ance directly and materially altered by slight differences in mechanical re.

02. Telephone transmitter. A telephone transmitter is a sound-operated or vibration-operated device designed to produce electroetic waves or vibrations which correspond to the sound waves or vibraactuating it.

303. Coefficient of coupling of a transformer. The coefficient of ling of a transformer at a given frequency is the ratio of the mutual dance between the primary and secondary of the transformer, to the re root of the product of the self-impedances of the primary and of the ndary.

304. Repeating coil. A term used in telephone practice meaning the s as transformer, and ordinarily a transformer of unity ratio.

305. Retardation coil. A retardation coil is a reactor (reactance used in a circuit for the purpose of selectively reacting on currents which at different rates.

Telegraphy

500. Relay. A relay is a device by means of which contacts in one uit are operated by a change in conditions in the same circuit or in one more associated circuits.

501. Polar relay. A polar relay is a relay which operates in response a change in the direction of the current in the controlling circuit.

502. Non-polar relay, or neutral relay. A non-polar relay is a ay which operates in response to a change in the strength of the current the controlling circuit, irrespective of the direction of the current.

503. Neutral relay. See non-polar relay.

504. Selector. A selector is a device which performs certain functions ch as causing an electric lamp to light, or an electric bell to sound, in sponse to a definite signal or group of successive signals received over a ntrolling circuit.

505. Direct-point repeater. A direct-point repeater is a repeater in hich the receiving relay controlled by the signals received over a line repeats ese signals into another line or lines without the interposition of any other peating or transmitting apparatus.

506. Concentrator. A concentrator is a traffic distributing device y means of which a number of telegraph or telephone lines, and connections o operating instruments are brought together at one point to facilitate heir interconnection at such times as signals or messages are to be transnitted from one to the other.

507. Transmitter. A transmitter is a device for effecting electrical hanges in a controlled circuit. The term transmitter is commonly applied principally to devices which in response to a controlling means effects in a main line telegraph circuit electrical changes necessary to send signals over the line.

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* Single frequency voltages and currents are here supposed to be represented by complex numbers. Their ratio is therefore a complex number.

† In telephone and telegraph usage, the terms "impedance coil," "inductance coil," "choke coil" and "reactance coil" are sometimes used in place of the term "retardation coil."

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12508. Synchronous system. A synchronous system of telegraphy is one in which the proper transmission and reception of signals is dependent upon the synchronous operation of similar commutators or other devices located at the sending and receiving stations of a circuit.

12509. Differential duplex. A differential duplex is a duplex system in which at each station one of two portions of the receiving instrument is connected in series with the line wire and the other in series with an artificial line of such electrical characteristics that the effects upon the receiver of currents passing through the main and artificial lines, as a result of outgoing signals, are neutralised.

12510. Bridge duplex. A bridge duplex is a duplex system in which the receiving instruments at each station is connected across two impedances, one in series with the line wire and the other in series with the artificial line in such manner that no electrical change in the receiver circuit is effected by outgoing signals.

12511. Half-set repeater. A half-set repeater is a repeater used for connecting together a simplex circuit and a duplexed circuit converting them into the equivalent of a single simplex circuit.

12512. Intermediate current supply. An intermediate current supply is an ungrounded source of current connected in series with a line wire at a station other than a terminal on a ground return telegraph circuit.

12513. Phantoplex circuit. A phantoplex circuit is a superposed circuit operated by alternating current over a simplex, duplex or quadruplex circuit operated from direct current sources.

12514. Spark condenser. A spark condenser is a condenser, with or without associated non-inductive resistance, connected with a pair of instrument contact points for the purpose of diminishing sparking at these points.

12515. Current margin. In a non-polar simplex system, the difference between the current flowing through a receiving instrument when operated to that flowing when not operated.

12516. Margin ratio. In a non-polar simplex system, the ratio of the current flowing through a receiving instrument when operated to that flowing when not operated.

12517. Percentage Margin. In a non-polar simplex, the current margin expressed as a percentage of the current flowing through the relay when operated.

12518. Main circuit. A main circuit is a major electrical circuit of a telegraph system and includes both transmitting and receiving devices.

12519. Local circuit. A local circuit is a circuit, within the limits of the station, usually controlled by a receiving instrument in a main circuit or controlling a transmitter effecting changes in a main line circuit.

CHAPTER XIII

STANDARDS FOR RADIO COMMUNICATION

General

This chapter has been mainly abstracted from the report of the standardisation committee of the institute of radio engineers, and is here included by permission, until further revised. For full particulars, see the I. R. E. Standardisation Committee report.

13000. Acoustic resonance device. One which utilises, in its operation, resonance to the audio frequency of the received signals.

13001. Antenna. A system of conductors designed for radiating or absorbing the energy of electromagnetic waves.

13002. Atmospheric absorption. That portion of the total loss of radiated energy due to atmospheric conductivity.

13003. Audio frequencies. Frequencies corresponding to the normally audible vibrations. These are assumed to lie below 10,000 cycles per second.

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13004. Capacitive coupler. An apparatus which, by electric fields joins portions of two radio-frequency circuits, and which is used to transfer electrical energy between these circuits through the action of electric forces.

13005. Coefficient of coupling (inductive). The ratio of the effective mutual inductance of two circuits to the square root of the product of the effective self-inductances of each of these circuits.

13006. Direct coupler. A coupler which magnetically joins two circuits having a common conductive portion.

13007. Counterpoise. A system of electrical conductors forming one portion of a radiating oscillator, the other portion of which is the antenna. On land stations a counterpoise forms a capacitive connection to ground.

13008. Damped alternating current. A damped alternating current is an alternating current whose amplitude progressively diminishes.

13009. Damping factor. The damping factor of an exponentially damped alternating current is the product of the logarithmic decrement and the frequency.

Let I_0 = initial amplitude
I_t = amplitude at the time t
e = base of Napierian logarithms
a = damping factor

Then: $I_t = I_0 e^{-at}$

13010. Detector. That portion of the receiving apparatus which, connected to a circuit carrying currents of radio frequency, and in conjunction with a self-contained or separate indicator, translates the radio-frequency energy into a form suitable for operation of the indicator. This translation may be effected either by the conversion of the radio frequency energy, or by means of the control of local energy by the energy received.

13015. Electromagnetic wave. A periodic electromagnetic disturbance progressing through space.

13016. Forced alternating current. A current, the frequency and damping of which are equal to the frequency and damping of the exciting electromotive force.

13017. Free alternating current. The current following any electromagnetic disturbance in a circuit having capacitance, inductance, and *less* than the critical resistance.

13018. Critical resistance of a circuit. That resistance which determines the limiting condition at which the oscillatory discharge of a circuit passes into an aperiodic discharge.

13019. Group frequency. The number per second of periodic changes of amplitude or frequency of an alternating current.

NOTE 1.—Where there is more than one periodically recurrent change of amplitude or frequency, there is more than one group frequency present.

NOTE 2.—The term "group frequency" replaces the term "spark frequency."

13020. Inductive coupler. An apparatus which, by magnetic forces, joins portions of two radio-frequency circuits and is used to transfer electrical energy between these circuits, through the action of these magnetic forces.

13025. Logarithmic decrement. The logarithmic decrement of an exponentially damped alternating current is the logarithm of the ratio of two successive current amplitudes in the same direction.

NOTE.—Logarithmic decrements are standard for a complete period or cycle.

Let: I_n and I_{n+1} be successive current amplitudes in the same direction.

d = logarithmic decrement

Then: $$d = \log_e \frac{I_n}{I_{n+1}}$$

13026. Radio frequencies. The frequencies are higher than those corresponding to the normally audible vibrations, which are generally taken as 10,000 cycles per second. See also Audio Frequencies.

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NOTE.—It is not implied that radiation cannot be secured at lower frequencies and the distinction from audio frequencies is merely one of definition based on convenience.

13027. Resonance. Resonance of a circuit to a given exciting alternating e.m.f. is that condition due to variation of the inductance or capacity in which the resulting effective current (or voltage) in that circuit is a maximum.

13028. Standard resonance curve. A standard resonance curve is a curve the ordinates of which are the ratios of the square of the current at any frequency to the square of the resonant current, and the abscissas are the ratios of the corresponding wave length to the resonant wave length, the abscissas and ordinates having the same scale.

13029. Sustained radiation. Sustained radiation consists of waves radiated from a conductor in which an alternating current flows.

13030. Tuning. The process of securing the maximum indication by adjusting the time period of a driven element. (See Resonance.)

13035. Wave-meter. A wave-meter is a radio-frequency measuring instrument, calibrated to read wave lengths.

13036. Decremeter. An instrument for measuring the logarithmic decrement of a circuit or of a train of electromagnetic waves.

13037. Attenuation, radio. The decrease with distance from the radiating source, of the amplitude of the electric and magnetic forces accompanying (and constituting) an electromagnetic wave.

13038. Attenuation, coefficient of (radio). The coefficient which, when multiplied by the distance of transmission through a uniform medium, gives the natural logarithm of the ratio of the amplitude of the electric or magnetic forces at that distance, to the initial value of the corresponding quantities.

13039. Coupler. An apparatus which is used to transfer radio-frequency energy from one circuit to another by associating portions of these circuits.

13040. Amplifier. An amplifier is an instrument which modifies the effect of a local source of energy in substantial accordance with the wave-form of the received energy, and gives out a wave of greater amplitude than that which it receives.

13041. Interference. See Par. **12045.**

13042. Phase angle defect. The phase angle defect of a condenser is the departure from quadrature of the phase difference between potential and current at terminals. This is sometimes called the phase angle of a condenser: although strictly speaking the phase angle of a condenser is 90 deg. less the phase angle defect, and is therefore exactly 90 deg. when the phase angle defect is zero.

13043. Impulse e.m.f. An e.m.f. the effective value of which becomes small compared with its maximum value in a time which is short compared with the duration of the current which it causes.

13044. Directive coefficient. The directive coefficient of a transmitting antenna at a given distance therefrom on the surface of the earth or sea, for a given wave length, is the ratio of average field intensity within an angle of stated degrees centered about the direction of maximum radiation, to the average field intensity in all directions.

13045. Directional selectivity. The directional selectivity of a receiving antenna at a given wave length is the ratio of the average e.m.f. induced in that antenna for waves of equal intensity coming from directions comprised within an angle of stated degrees centered about the direction of best reception, to the average e.m.f. induced in the antenna for waves of equal intensity coming from all directions.

13046. Radiation efficiency. The radiation efficiency of an antenna at a given wave length is the ratio of radiation resistance to the antenna resistance.

13047. Selectivity. The (overall) selectivity of a receiving system is the product of the several selectivities of that system.

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. **Average selectivity.** The average selectivity of a receiving sys-
ıe *n*th root of the product of the *n* selectivities of that system.

9. Radio-frequency selectivity. The radio-frequency selectivity
ple element* of a receiving system is the ratio of resonant response
ıs of effective voltage or current measured at the indicator) to the
)nant response when the radio-frequency portions of the elements
system are detuned by 1 per cent. of the resonant frequency.

CHAPTER XIV

DARDS FOR PRIME MOVERS AND GENERATOR UNITS

General

). **Regulation of steam engines, steam turbines and internal**
ıstion engines. In steam engines, steam turbines and internal
tion engines, the percentage speed regulation is usually expressed as
centage ratio of the maximum variation of speed, to the rated-load
ı passing slowly from rated-load to no-load (with constant conditions
ıupply).

1. **Fluctuation of steam engines, steam turbines and internal**
ıstion engines. The percentage fluctuation of a steam engine,
turbine or internal combustion engine, is the immediate percentage
regulation corresponding to a sudden change from rated-load to
l.

2. **Regulation of hydraulic turbines.** In a hydraulic turbine, or
vater motor, the percentage speed regulation is expressed as the per-
ə ratio of the maximum variation is speed in passing slowly from rated-
› no-load (at constant head of water), to the rated-load speed.

3. **Regulation of generator units.** In a generator unit consisting
nerator combined with a prime mover, the speed or voltage regulation
e based upon constant conditions of the prime mover; *i.e.*, constant
pressure, head, etc. It includes the inherent speed variations of the
mover. For this reason, the regulation of a generator unit is to be
uished from the regulation of either the prime mover, or of the gen-
combined with it, when taken separately.

)10. **Variation in prime movers.** The variation in prime movers
do not give an absolutely uniform rate of rotation or speed, as in
ɔcating steam engines, is the maximum angular displacement in posi-
f the revolving member expressed in degrees, from the position it
occupy with uniform rotation, and with one revolution taken as 360
See Par. 4068.

11. **Pulsation in a prime mover, or in the alternator connected**
to. The pulsation in a prime mover, or in the alternator connected
o, is the ratio of the difference between the maximum and minimum
ties in an engine-cycle to the average velocity.

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erican Society of Mechanical Engineers: Boiler Code.

Foreign

tish Engineering Standards Association: Standard Electrical Pressures
ew Systems and Installations (Low and Medium Pressures); Steam
nes for Electrical Plants; Report on Reciprocating Steam Engines for
rical Purposes.

. simple element as referred to a combination of an inductance, a capaci-
and optionally a resistance; or their mechanical equivalent.
f *p* is the number of pairs of poles, the variation of an alternator is *p*
the variation of its prime mover, if direct connected, and *p n* times the
tion of the prime mover if rigidly connected thereto in such a manner
the angular speed of the alternator is *n* times that of the prime mover.

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CHAPTER XV

STANDARDS FOR TRANSMISSION LINES AND DISTRIBUTION LINES

NOTE.—For flash-over tests of insulators, see foot-note to Par. 2361.

General

15000. Regulation of transmission lines, feeders, etc. The regulation of transmission lines, feeders, etc., is the change in the voltage at the receiving end between rated non-inductive load and no-load, with constant impressed voltage upon the sending end. The percentage regulation is the percentage change in voltage to the normal rated voltage at the receiving end.

CHAPTER XVI

MISCELLANEOUS STANDARDS

HEATING DEVICES

16000. Value of alternating-current test voltage for household devices. Heating devices taking not over 660 watts, intended solely for operation on supply circuits not exceeding 275 volts, shall be tested with 500 volts at operating temperature.

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SECTION 25

GENERAL ENGINEERING ECONOMICS AND CENTRAL STATION ECONOMICS

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(*Numbers refer to Paragraphs*)

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SECTION 25

GENERAL ENGINEERING ECONOMICS

BY FRANK F. FOWLE, S.B.

GENERAL DEFINITIONS

1. **Engineering** is defined in its modern sense by Webster's New International Dictionary as, "The art and science by which the mechanical properties of matter are made useful to man in structures and machines." A broader and perhaps better definition is, "The art of organizing and directing men and of controlling the forces and materials of nature for the benefit of the human race." Telford defined an engineer as one who applies the forces of nature to the service of man (*Trans.* A. I. E. E., Vol. XXII, 1903, p. 620).

2. **Branches or subdivisions of engineering.** Originally engineering was regarded as having but two subdivisions or branches: (1) military engineering, or the design and construction of offensive and defensive military works; (2) civil engineering, or the design and construction of public works, roads, bridges, canals, tunnels, lighthouses, etc. This distinction has long since become obsolete, and engineering is now such an indispensable factor in our modern complex civilization, that it is necessary to recognize a great many different fields or branches of it. To classify these in detail is difficult, because there is frequently no sharp line of demarcation between one field and another, and different fields frequently overlap one another.

The well-recognized major divisions of engineering are civil, mechanical, electrical, and chemical; each of these broad fields is subdivided into many branches and specialties, some distinct and some overlapping. Examples of these subdivisions are hydraulic, highway, structural, steam, refrigerating, illuminating, telephone, radio, electrochemical, sanitary, metallurgical, gas, aerial engineering, etc. These major and secondary classifications do not define all of the recognized fields, however, because there are numerous industries which are so important and so broad in their scope as to have created special engineering fields, combining in practically every case two or more of the major divisions or subdivisions given above. Among these can be named railroad, marine, mining, water-works, central station, municipal, industrial, naval, ordinance engineering, etc.

Thus there is no simple classification of the different branches of engineering which readily defines or embraces the whole field. Yet all the branches of engineering have much in common, in the respect that the underlying technical foundation in every case consists of a thorough knowledge of physics, chemistry and mathematics.

3. **Economics or political economy** is defined as the science of wealth, and is concerned with the general laws affecting the production, distribution, exchange and consumption of wealth. It is not in place to go into the abstract general principles of the subject here; several of the leading authorities are named below* for the benefit of any who wish to study the

* Walker, F. A. "Political Economy;" H. Holt & Co., New York, 3rd ed., 1888.
Hadley, A. T. "Economics;" G. P. Putnam's Sons, New York, 1897.
Ely, R. T. "Outlines of Economics;" The MacMillan Co., New York, 1908; rev. ed.; see Bibliography in Appendix B.
Taussig, F. W. "Principles of Economics;" The MacMillan Co., New York, 1911, 2 vol.
Seligman, E. R. A. "Principles of Economics;" Longmans, Green & Co., New York, 3rd. ed., 1907; see "Suggestions For Students and General References," pp. XVII to L.
Marshall, A. "Principles of Economics;" The MacMillan Co., New York, 1907; 5th ed.

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eneral subject. Those principles of economics which are especially useful the engineer are covered or touched upon in the succeeding treatment.

4. Engineering economics may be defined as that field or body of knowledge which is concerned with the *economic* results of engineering, and the pplication of the principles and laws of economics to engineering undertakings. Since the purpose of all engineering is avowedly utilitarian, it eems unnecessary to offer proof that engineering should invariably justify self upon economic grounds. Obviously no contemplated engineering roject can be reasonably sure of success, however sound it may be upon urely technical grounds, until it has been most carefully considered on conomic grounds and the conclusion reached that barring unforeseen casualties it will become a paying and profitable enterprise.

5. The fundamental elements of engineering economics may e grouped into four broad classes, with certain subdivisions, as indicated elow. This classification is here presented for the first time and hence it hould be regarded as tentative. The main thought, however, is to make s clear as possible the principal economic considerations in engineering ork as they exist to-day.

The Elements of Engineering Economics	Cost Analysis	Principles of accountancy Capital and operating charges Total annual charges Costs per unit Fixed and variable costs Cost balance
	Social-Economic Investigations	Traffic analysis Statistics of consumption Probable future development
	Valuation of Property	Purchase or sale Rate making Taxation Issuance of securities Adjustment of book values
	Rate Making	Public utilities Common carriers

The skeleton definition of engineering economics given above should be nterpreted in a somewhat liberal sense; the predominant idea to be emhasized is the unavoidable contact of the modern engineer with countless economic questions involving cost, price and value, and those social-economic uestions connected with the operation and development of engineering rojects directly affecting the public or the public welfare.

The subsequent presentation of the subject is not offered in the sense that t is complete or exhaustive; on the contrary, it is somewhat fragmentary, ut has been prepared with the object of making it as useful as possible.

VALUE, PRICE AND COST

6. Value defined in the economic sense is power in exchange, or purhasing power. Ely states that value in the generally accepted sense is xchange value, or objective value as distinguished from subjective value. The measure of importance attached to a commodity or article by some one ndividual is subjective value, and obviously may differ in extreme degree rom the value placed upon the same commodity or article by some other erson. Hadley states that value is essentially an ethical term and therefore there may be as many theories of value as there are views of business ethics; he also points out that while the term value may be used in the sense of utility, it ordinarily means the proper and legitimate price, or an estimate of what the price ought to be. Walker drew a very careful distinction between value and utility, the latter being always present where there is value, whereas utility alone does not invariably imply value in the economic sense. Utility does not imply value in the economic sense until it is coupled with desire. Among other elements which go to comprise economic value, the factors of time, place, cost and demand are of major importance. Therefore in speaking of value it is essential to employ such qualifying adjectives or phrases as will serve to make clear the particular kind of value in mind. The term value should never be confused with the terms price or cost, since the several meanings are distinctly different.

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7. Price is exchange value or purchasing power expressed in terms of some one article or commodity, which is usually money. It is important to recognise that price and value are not synonymous terms, although in ordinary commercial usage the term value is quite generally used in the sense of the reasonable price, or what the price ought to be under the ruling conditions. The natural or normal price is the price which is proportional to the cost of production; Adam Smith called the price in terms of money the nominal price, and the price in terms of units of labor or services the real price. Price and cost are not synonymous terms; for instance, the price paid for an article represents the cost to the purchaser, but not to the seller. It is therefore important to preserve this distinction in general. Generally speaking, price means the amount of money actually asked or paid for the article or thing in question.

8. Competitive regulation of prices. Except for those commodities or services vested with a public interest, the charges for which are regulated by statute, prices are regulated by the law of supply and demand, under free competition. In other words, prices are regulated by economic laws except for certain classes of things which have their prices regulated by statute.

9. Price regulation by statute. In the case of services or commodities which, generally speaking, are necessary to the public convenience and welfare, such as transportation, water supply, gas, electrical energy, communication, etc., it is now universally accepted that the public has the inherent right to regulate the prices or rates therefor. Such regulation is provided for under the Interstate Commerce Act and the public utility laws of the various states. The broad general principles involved in such regulation are three in number: (1) every price or rate is subject to the test of reasonableness, from the standpoint of all the parties involved; (2) under like conditions of service or supply there shall be no discrimination as to price; (3) all who come must be served. For references to the extensive literature on the subject of public utility regulation, see the Bibliography, Par. 88, 189.

10. Cost is what the owner of a thing actually paid for it, or his total outlay for the same, in wages, materials and expenses. When the term cost is employed in its broadest sense, it is commonly understood to include not only wages, materials and expenses, but such charges as interest, taxes, insurance and depreciation on the plant required to produce the article or service in question, and perhaps also a certain allowance for profits in addition to the foregoing. Thus it is very essential, in discussing the cost of a thing, or in comparing different costs, to define the elements which cost is understood to include. In most cases it is desirable to employ the term cost in connection with a prefix or adjective which defines it so clearly as to preclude confusion or misunderstanding; for example, labor cost, fuel cost, productive cost, selling cost, distribution cost, etc.

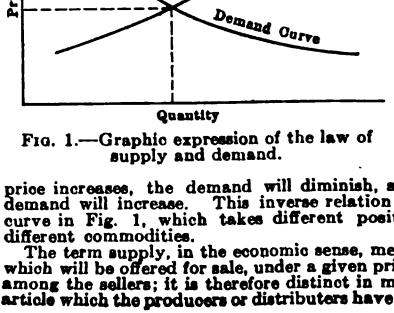


FIG. 1.—Graphic expression of the law of supply and demand.

11. The law of supply and demand. The term demand, in the economic sense, means the quantity of an article which will be purchased at a given price, assuming free competition among the buyers. If the price increases, the demand will diminish, and if the price decreases the demand will increase. This inverse relation is expressed by the demand curve in Fig. 1, which takes different positions and characteristics for different commodities.

The term supply, in the economic sense, means the quantity of an article which will be offered for sale, under a given price, assuming free competition among the sellers; it is therefore distinct in meaning from the stock of the article which the producers or distributers have on hand, available for offering

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n the market. When the price increases, the supply will increase; and con-ersely, when the price drops, the supply will fall. This relation is expressed y the supply curve in Fig. 1, which occupies different positions for different ommodities.

In a stable market the supply will equal the demand, at the normal price. f the price is forced upward, the demand will fall and the supply will in-rease; the attendant reaction will naturally tend to restore the normal onditions. If the price is manipulated downward the demand will increase, ut the supply will diminish; and the attendant natural reaction is again uch as to tend toward the restoration of normal conditions.

Should there come about a permanent condition in the market, resulting n greater normal demand, the position of the demand curve will shift in uch manner that the demand at the former normal price will be greater han before. The result will be a higher normal price at increased normal uantity or sales. In like manner, a permanent reduction in demand will esult in a lower normal price, at diminished normal quantity. A permanent hange in the supply, such as might result from a decrease in the sources of aw materials, or, on the other hand, a discovery of new sources of raw naterials, will likewise cause the supply curve to shift to a new position.

Generally speaking, a condition of gradually rising normal demand is losely succeeded by a rise in prices, until the demand reaches an even level. A falling demand is similarly followed by diminishing prices, until the emand strikes bottom. Such phenomena will be observed quite generally n studying the prices of any article through a series of years.

CAPITAL, RENT AND INTEREST

12. Wealth in the economic sense may be defined as all property which ossesses money value or economic utility. In the broadest possible sense t means an abundance of things which are objects of human desire, but specially an abundance of worldly estate or riches, such as land, goods, money nd securities.

13. Property is defined by Webster as follows: The exclusive right to ossess, enjoy, and dispose of, a thing; ownership; in a broad sense, any aluable right or interest considered primarily as a source or element of vealth; practically all valuable rights except, generally, those involved in ublic or family relations; various incorporeal rights, patents, copyrights, ights of action, etc.; anything, or those things collectively, in or to which a nan has a right protected by law. Property is commonly regarded as omprising two kinds: real property, or land, buildings, fixed plant and mprovements in connection therewith; personal property, or furniture, ools, implements, live stock, money, securities, etc. There is also a more nodern distinction, as between tangible and intangible property: the former ncludes real and personal property which exists in tangible physical form; ntangible property comprises rights, franchises, good will, going-concern alue, patents, copyrights and contracts.

14. Capital may be defined in the economic sense as a stock of accumu-ated wealth; or the amount of property owned by an individual or a corpora-ion at a specified time, in distinction from the income received during a iven period. Capital may be in the form of money, or some readily salable rticle for which there is a constant and general demand, in which case it is aid to be liquid capital; or it may be in the form of property which is not eadily salable on sudden notice, such as land, buildings, or manufacturing lant, in which case it is termed invested capital. In other words, liquid apital can be readily and quickly converted into money if it is not already uch, whereas invested capital usually cannot.

15. Money is a common medium of exchange, issued by duly constituted uthorities, and, as such, is a commodity the same as any other article which asses frequently from hand to hand in trade or exchange. Therefore, eing a commodity, the price of money is regulated by the law of supply and lemand. Thus when money is scarce and the demand normal, or heavy, it vill command a premium; conversely, if money is overplentiful and the de-nand low, it can be had at a discount. While true in theory, such fluctua-ions in the price of money from its face or par value, are disturbing to trade nd therefore undesirable; one of the fundamental purposes of our present urrency system is to provide elasticity in the supply of money, in order uitably to meet changes in the demand for it and avoid both premiums and

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discounts. To the end that money may be kept on a stable basis, it is usually founded upon a standard comprised of one of the rare or precious metals; thus the gold standard of value is recognized in the civilized countries the world over, and is the basis of the money in our own country.

16. Rent is defined as the price paid for the services or use of land; this is the definition usually given in Economics. In the ordinary commercial sense, rent is the price paid for the use of real property, including land and the buildings and improvements thereon. Under the latter definition, the term rent includes both ground rent and capital rent. The term capital rent is synonymous with interest, defined in the next paragraph.

17. Interest is the price paid for the services or use of capital; or the rent for the use of capital. Economists distinguish two kinds of interest: loan interest, or the rent for borrowed capital; imputed interest, or that increment in the price paid for a commodity or a service which recompenses the vendor for the use of his capital in the operation. Universal custom has established the practice of basing the interest charge or rental on a certain percentage, per unit of time, applied to the principal or capital.

Ordinary interest is usually collected with the repayment of the principal, or at stated periods during the term of the loan, say annually, or semi-annually. Another form of interest is termed discount, or banker's discount; this differs from ordinary interest in the respect that it is collected in advance by deducting it from the principal of the loan when handed to the borrower.

18. The risks of investment. Capital, being a commodity in the economic sense, is subject to the law of supply and demand. Those persons possessing idle capital are always seeking a market for it, or some use in return for which it will yield interest; persons having business opportunities but lacking the necessary capital to embark in their ventures, are naturally seeking those who have capital to invest. The investor or loaner of capital is concerned with both the safety of his principal and the rate of interest yield, and naturally seeks the highest obtainable interest rate consistent with the risk he is willing to assume for the return of his capital at some stated time or on demand. It is a fundamental principle that the interest rate demanded by capitalists increases with the degree of risk assumed on the principal; and conversely, the less the risk, the lower is the interest rate tendered by borrowers. Thus it can be said, in general, that the commercial rate of interest charged for the use of capital contains two components; one of these is the true interest, and the other is virtually a premium on insurance against loss of the principal.

19. Legal rates of interest under the numerous state laws are given in the appended table.

States and territories	Legal	Contract	States	Legal	Contract	States	Legal	Contract
Alabama	8	8	Kansas	6	10	New York	6	6
Alaska	8	12	Kentucky	6	6	N. Carolina	6	6
Arizona	6	any	Louisiana	5	8	Ohio	6	8
Arkansas	6	10	Maine	6	any	Okla. Ter	7	12
California	7	any	Maryland	6	6	Oregon	6	10
Colorado	8	any	Mass.	6	any	Penna.	6	6
Conn.	6	6	Michigan	5	7	R. Island	6	any
Dakota, N.	7	12	Minnesota	6	10	S. Carolina	7	8
Dakota, S.	7	12	Mississippi	6	10	Tennessee	6	6
Delaware	6	6	Missouri	6	8	Texas	6	10
Dist. of Col.	6	6	Montana	8	any	Utah	7	any
Florida	8	10	Nebraska	7	10	Vermont	6	6
Georgia	7	8	Nevada	7	any	Virginia	6	6
Idaho	7	12	New Hamp.	6	6	Wash't'n.	6	12
Illinois	5	7	N. Jersey	6	6	W. Virginia	6	6
Indian Ter.	6	8	N. Mexico	6	12	Wisconsin	6	10
Indiana	6	8				Wyoming	8	12
Iowa	6	8						

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20. Interest rates vary to a considerable extent, depending upon the class of investment. U. S. Government bonds pay different rates, from 2 per cent. to 4 per cent.; savings-banks deposits, from 3 to 4 per cent.; checking deposits in banks, above a certain minimum amount, frequently draw 2 per cent. on daily balances; certificates of bank deposit, or time deposits, 3 per cent.; railroad and public utility bonds, from 3.5 to 6 per cent.; industrial bonds, 5 to 7 per cent.; short-term notes of railroads and public utilities, to 6 per cent.; real-estate mortgages, 5 to 6 per cent.; railroad and public utility stocks, whatever may be earned, but seldom in excess of 8 per cent.

21. Compound interest is based upon the computation of simple interest for stated periods and the addition of the interest to the principal at the end of each period, thus enlarging the principal for each consecutive period, progressively. Let

P = the principal in dollars.

n = the number of years for which the compound interest is to be computed.

t = the ratio of 1 year to the period during which simple interest is computed; thus if compounded annually, $t = 1$ and if compounded semi-annually, $t = 0.5$.

r = the annual percentage rate of interest expressed as a decimal; thus if the rate is 6 per cent., $r = 0.06$.

S = the amount of P dollars at compound interest for n years, compounded at intervals of t years, at the annual rate r

The formula for calculating S is as follows:

$$S = P\,(1+tr)^{\frac{n}{t}} \qquad \text{(dollars)} \qquad (1)$$

This can also be expressed in another form

$$\log S = \log P + \frac{n}{t}\log\,(1+tr) \qquad (2)$$

The latter form indicates the manner of calculating problems; in most cases the interest is compounded annually, which makes $t = 1$.

22. Present worth of a future lump payment. If the sum of S dollars is due at the end of n years, the amount which would have to be set aside at the present date, compounded at intervals of t years at the annual interest rate r (decimally expressed), is expressed by the following formula:

$$P = \frac{S}{(1+tr)^{\frac{n}{t}}} \qquad \text{(dollars)} \qquad (3)$$

This can also be expressed in a form suitable for numerical calculation:

$$\log P = \log S - \frac{n}{t}\log\,(1+tr) \qquad (4)$$

The symbols used have the same significance as stated in Par. **21.**

23. Annuities. An annuity is a fixed sum of money payable at equal intervals of time (see Wells, W. "College Algebra;" chapter on "Compound Interest and Annuities"). In most discussions of the subject it is assumed that the payments are made annually and the interest compounded annually. When an annuity is defined as beginning at a certain date, the first payment will fall due 1 year from that date.

24. The present worth of an annuity of A dollars per annum, commencing at once and continuing for n years, allowing interest compounded annually at the annual rate r (decimally expressed), may be calculated from the following formula:

$$P = \frac{A}{r}\left[\frac{(1+r)^n - 1}{(1+r)^n}\right] \qquad \text{(dollars)} \qquad (5)$$

The present worth of a perpetual annuity, commencing at once, is equal to A/r.

The present worth of an annuity to commence after m years and then continue for n years, is expressed by the formula,

$$P = \frac{A[(1+r)^n - 1]}{r(1+r)^{m+n}} \qquad \text{(dollars)} \qquad (6)$$

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The present worth of a perpetual annuity to commence after n years, is

$$P = \frac{A}{r(1+r)^n} \qquad \text{(dollars)} \tag{7}$$

25. A sinking fund is one to which equal annual payments are made, compounded at stated intervals, for the purpose of producing a certain predetermined sum at the end of a given period. Sinking funds are quite commonly established for the purpose of retiring bond issues or loans at maturity; they are also established occasionally for the purpose of creating depreciation reserves.

If it is desired to have a sum of S dollars at the end of n years, created from n equal payments, one at the end of each year, compounded annually at the annual interest rate r (decimally expressed), the amount of each annual payment must be that found from the following formula:

$$p = \frac{rS}{(1+r)^n - 1} \qquad \text{(dollars)} \tag{8}$$

Such a fund does not accumulate uniformly, but at a progressively increasing rate, slowly at first, and rapidly toward the end of the period; this effect becomes more pronounced as the period lengthens. At the end of m years the total amount in the fund bears to the ultimate fund (n years) the ratio expressed by the formula,

$$\frac{(1+r)^m - 1}{(1+r)^n - 1} \tag{9}$$

This formula is sometimes made use of in determining the percentage of present condition in appraising depreciated properties (Par. 64).

26. Sinking-fund table. The table given below is based on Eq. 8 in Par. 25, and shows the sum which must be set aside at the end of each year, for n years, at various rates of interest, compounded annually, to produce the total sum of one dollar at the end of the period. The values given in the table were taken from a more comprehensive table given by Henry Floy in his work, "Valuation of Public Utility Properties" (McGraw-Hill Book Co., New York, 1912), Chap. VIII.

(Amounts stated in dollars)

Years	Annual rate of interest; per cent.				
	2	3	4	5	6
1	1.000	1.000	1.000	1.000	1.000
2	0.4950	0.4926	0.4902	0.4878	0.4854
3	0.3268	0.3235	0.3203	0.3172	0.3141
4	0.2426	0.2390	0.2355	0.2320	0.2286
5	0.1922	0.1884	0.1846	0.1810	0.1774
6	0.1585	0.1546	0.1508	0.1470	0.1434
8	0.1165	0.1125	0.1085	0.1047	0.1010
10	0.09133	0.08723	0.08329	0.07950	0.07587
12	0.07456	0.07046	0.06655	0.06282	0.05928
15	0.05783	0.05377	0.04994	0.04634	0.04296
20	0.04116	0.03722	0.03358	0.03024	0.02718
25	0.03122	0.02743	0.02401	0.02095	0.01823
30	0.02465	0.02102	0.01783	0.01505	0.01265
40	0.01656	0.01326	0.01052	0.008278	0.006462
50	0.01182	0.008866	0.006550	0.004777	0.003444
75	0.005855	0.003668	0.002229	0.001322	0.0007687
100	0.003203	0.001647	0.0008080	0.0003831	0.0001774

ANNUAL CHARGES

27. Two general classes of costs. In most enterprises there are two general classes of expenditures or costs, namely: (1) expenditures for plant or property, or improvements thereto, all constituting **additions to capital**;

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(2) expenditures for salaries, wages, rents, taxes, insurance, depreciation, repairs, supplies, etc., all constituting charges to operation, or **operating expenses**. The distinction between these two classes of costs is fundamental in its importance.

28. Cost comparisons are of two kinds: (1) comparisons of capital costs, or construction costs; (2) comparisons of operating costs. When comparing one plant with another, as to overall results, it is necessary to reduce all costs to one basis; this is most frequently done by comparing the total annual charges (Par. **29**), but in some instances the operating expenses (excluding interest and profits) are capitalized at the prevailing interest rate and added to the capital or investment. The latter method is rarely used.

29. The total annual charges may be defined as the sum of all operating expenses (Par. **27**) plus interest and profit on the investment or capital; or the total charge for operation. The total annual charges may be classified as shown below.

- Total annual charges for operation
  - Investment costs
    - Taxes
    - Insurance
    - Depreciation
    - Maintenance
    - Interest
    - Profits
  - Production costs
    - Traffic
    - Transportation
    - Operating
    - Commercial
    - General

These charges are defined in the succeeding paragraphs.

30. Taxes constitute a charge based on the assessed value of the property and require no explanation. This charge varies from about 1 per cent. to 2 per cent. per annum on the capital invested in physical or tangible property.

31. Insurance can be defined as a cooperative method of distributing the burden of losses or casualties. The annual assessments or rates are determined by actuaries who apply the theory of probability to the problem of determining the probable risk of loss or damage, based upon the statistics of a large number of past losses. There are many different kinds of insurance, such as life, health, fire, boiler, accident, marine, employers' liability, automobile, plate glass, burglar, hurricane, cyclone, etc. The insurance rate is usually based on a percentage of the investment in insured property, or face value of the total risk, per unit of time or per annum.

32. Depreciation is fully covered in another portion of this section; see Par. **41**, *et seq.* It is quite as much an expense of operation as the cost of labor, supplies and other items which are currently paid by the day, week or month.

33. Maintenance defined in its broadest sense means upkeep of all kinds, including both repairs and renewals, but in the technical sense in which it is usually employed it means repairs exclusively. The repair charge is frequently reduced to terms of a percentage of the capital invested in plant, or the original cost of the plant.

34. Interest has been defined at length in Par. **17** to **20**, and need not be further considered here.

35. Profits represent a return on the investment over and above the normal rate of interest. For instance, a return of 8 per cent. has been held reasonable in the case of certain public utilities, on the theory that in addition to interest at a rate, say, of 6 per cent., the investor is entitled to a profit of 2 per cent. as an inducement to himself and others to engage in the particular class of business in question. The term profit is often employed, however, in the sense of including true interest in addition to true profit.

36. Investment costs are those, as the name implies, which bear some direct ratio or proportion to the investment. They are defined in Par. **29** to **35**, above. In the case of maintenance expense, there is probably some portion of it, but not all, which is more nearly a production expense than an investment expense; this seems to be obviously true, because of the fact that

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certain repairs depend upon the amount of use, and increase therewith, as in the case of machinery. The investment costs are sometimes termed **fixed charges.**

37. Production costs, defined in Par. **29** as including traffic, transportation, operating, commercial and general expenses, can be said to include in general all other operating expenses not included under the definition of investment costs. The classification of production costs will follow, as a rule, the accounting classification for the utility or common carrier under consideration.

38. How to determine the annual charges. The determination of annual charges, for the purposes of cost analysis, rate making, or comparison, should be made as far as possible with the aid of the corporate accounts or books of the company, showing every detail of the business. This will usually insure that no element of cost is overlooked, and will substitute fact for assumption in every case where dependable facts are available. When the corporate books are not available, general experience and special knowledge of the class of business in question, are the only means at hand.

39. Constant and variable expenses. For the purposes of rate making it is frequently convenient to treat all operating charges as divisible into two classes: (1) constant expenses, or all expenses which do not vary with the rate of production or output; (2) variable expenses, or all expenses which change substantially in direct proportion with the output.

40. Cost balance. One of the most important problems in engineering economics is to determine whether a given operation or service is secured in the most economical manner. Otherwise expressed, this is the problem of determining the particular set of conditions which makes the total annual charge a minimum. Such a problem is usually complicated by the presence of numerous variables, and it becomes impracticable to lay down any brief general rules; each problem is likely to represent a class by itself.

A good example of this problem is that of determining the particular size of conductors which will insure the transmission of electrical energy, under a given set of conditions, at a minimum annual charge. This problem was first solved by Sir William Thompson (Lord Kelvin) and the theorem which he deduced is known as Kelvin's Law; see Sec. 11, 12 and 13.

DEPRECIATION

41. Depreciation is defined by Webster* as follows: A falling of value of money, a reduction or loss in exchange value or purchasing power, especially with reference to the face value; a lessening in price or estimated value, lowering of worth. In the case of property, there are some kinds whose exchange value seldom decreases, and is more likely, perhaps, to increase; there are other kinds which inevitably depreciate, and finally reach a certain small minimum value or possibly cease to possess any value whatever. The engineer is concerned for the most part with those kinds of property which are perishable, in the ultimate sense, and which deteriorate through physical causes, or through the loss of economical usefulness.

42. The necessity for recognising depreciation is two-fold. In the first place, perishable property will ultimately reach a point at which it possesses only a certain minimum or residual value, or else it will cease to have any value whatever, in consequence of having outlived its usefulness. Then replacement will become necessary, and in order to provide the requisite funds without increasing the investment or drawing upon capital, or making an excessive charge against operating expenses, it is desirable to lay aside each year a uniform amount for the creation of a depreciation reserve which will equal the total cost of renewal at the end of the life period.

In the second place, when perishable property is bought or sold during its life period, it is not as a rule considered to be worth its original value, because it has depreciated in the meantime; the present worth, on any given date, is said to be the original worth less the accrued depreciation to such date.

The two phases of the depreciation problem are, therefore: (1) To ascertain the annual rate of depreciation; (2) to ascertain the accrued depreciation on any given date, or at any given age.

* New International Dictionary.

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). The two classes of depreciation usually recognised are physical reciation and functional depreciation. These are defined in the next ieeding paragraphs.

4. Physical depreciation is the result of age, wear and tear, corrosion, decay. This form of depreciation is constantly in progress; the rate of progress depends upon the conditions of service or use, protection from aging elements, and the degree of care exercised in making prompt airs when necessary. This rate of course varies greatly with different ns of machinery, apparatus, plant, etc.

5. Functional depreciation is the result of failure to function properly, onsequence of lack of adaptation to the service demanded. It has two ıcipal causes, inadequacy and obsolescence.

6. Inadequacy is the result of unexpected or premature growth in the nand for service, requiring enlarged capacity which can be provided only removing the old plant or equipment to make way for new before physical reciation has run its full course. Depreciation resulting from this cause ally makes it imperative to replace equipment or plant sooner than otherе, but the displaced equipment is sometimes useful for a further period e-installed in a new location or in some other plant where its capacity is ted to the demands for service. One of the functions of sound engineering, ourse, is to study the probable future demands and so arrange a plant installation that new units can be provided as occasion may demand, hout disturbing the units already in operation. In other words, part of inherent economy in efficient engineering consists in securing if possible maximum physical life from any piece of plant or apparatus, unless, of ırse, it appears conclusively that the total annual charges (Par. **29**) will be ually lessened by deviating to some other plan or policy. It is conceivе, for instance, that the maximum physical life will exceed the economical , but this is predicated upon the assumption of a progressively diminish- efficiency with increasing age, attended by a marked increase in the total nual charges per unit of production or output before approaching the end the maximum physical life.

17. Obsolescence is that form of functional depreciation which results m new inventions or radical improvements in the art, causing a set-back present methods or machinery in the scale of efficiency, or creating new mands which it was not possible to serve under the past state of the art. hether all forms of obsolescence, or allowances for their probable occurıce and effect, should be included in depreciation is perhaps an open queen. Many advances in the art relate wholly to improvements in efficiency reductions in the cost of production. When comparing a new and proved machine with one of obsolete type but not yet worn out in the ysical sense, the question whether the new shall immediately supplant e old is usually regulated by the consideration whether the saving in total nual charges (Par. **29**) resulting from the substitution will extinguish the maining service value of the old machine within a reasonable period, or uch sooner than the expiration of the probable life period of the new achine. Thus there are certain types of cases in which obsolescence is not proper charge against depreciation, but should be amortized (Par. **68**) rough the application of those annual charges which represent the savings operation secured by discarding obsolete machinery or plant. Cases of ıe latter type are probably typical, as a rule, of the greater number of adıces in the art; whereas that type of obsolescence which makes it almost ıperative to discard the old for the new, springs into existence with the latively infrequent advances in the arts which are fundamental or revoluonary in character, as distinguished from those advances which can be assed as mere improvements of things which are already old in the arts.

18. The insurance element in depreciation. It is almost self-evident ıat any provision in depreciation for probable future inadequacy and obsoscence partakes of the nature of insurance to cover a risk. In this sense, ierefore, provisions for future inadequacy and obsolescence are, in reality, surance charges, and not depreciation in the technical sense—at least not the physical sense. Such provisions should be based, therefore, upon the w of probability applied to the statistics of past occurrences with respect the abandonment of plant or machinery strictly on account of inadequacy ıd obsolescence. This mode of procedure will develop the monetary

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value of the risk, and the annual insurance charge in terms of a percentage of the investment or cost of the plant; the insurance charge should be added to the annual percentage charge for depreciation of a purely physical character.

Another element sometimes included in the gross charge for depreciation is the insurance increment to cover losses from probable plant casualties such as fires, floods, cyclones, storms, earthquakes, etc. This again involves the application of the law of probability, to the statistics of past casualties to plant; the necessary annual insurance charge, determined in terms of a percentage of the plant investment or cost, should be added to the other percentage elements comprising the gross annual allowance for depreciation. Of course these charges which partake purely of insurance, can be segregated from the charges for physical depreciation, if desired, and there would be some advantage in so doing, from the standpoint of cost keeping and business administration.

49. The terms employed in discussing depreciation are defined in the following Par. 50 to 60.

50. Original cost or investment (I) means the total actual outlay or expenditure for the physical plant, installed and in readiness for service; it is also known as the physical cost. It includes as a rule all expenditures which can be classed as construction costs, but none of the so-called intangible property such as franchises, good will, patent rights, licenses, contracts, cost of establishing the business, or going value.

51. Salvage or scrap value (S) is the amount realized from the sale of worn-out or abandoned plant for what it will bring as junk or second-hand materials.

52. Cost of removal (R) is the cost of labor and other expense incidental to the removal of worn-out or discarded plant, to make way for the new plant which will replace it.

53. Service or wearing value (W) is the sum of the original cost plus the cost of removal, less the salvage value, expressed by

$$W = I + R - S \qquad \text{(dollars)} \qquad (13)$$

This is the net depreciable value of the plant, or the sum of money which will be required to replace the plant when it becomes useless, provided that the cost of labor, materials and equipment remains unchanged.

54. Realized depreciation is the term applied, in accounting, to the actual sum or amount charged to the depreciation reserve when plant is actually displaced or abandoned. In amount it is identical with the wearing value, W.

55. Accrued depreciation (A) is the total or cumulative depreciation of the plant on any given date, expressed in the same units of value measured as the original cost, or in dollars. The accrued depreciation increases in amount as the plant grows older, and finally, at the end of the physical life, becomes equal to the wearing value, W.

56. Present worth (P) is the difference between the original cost (I) and the accrued depreciation (A), expressed by $P = I - A$.

57. The life (l) of a plant is always expressed in years. Unless otherwise qualified, the estimated life is usually stated for the conditions of service which the plant or apparatus in question will be required to meet. In some cases, the estimated life includes allowances for probable inadequacy and obsolescence, and in such instances will be less than the physical life which ought to be expected. For tables of **life expectancy** of different kinds of machinery and plant, see other sections of the Handbook dealing with the same; also Foster, H. A. "Engineering Valuation of Public Utilities and Factories;" and Floy, H. "Valuation of Public Utility Properties;" also see Sec. 10, subsection on "Power Plant Economics."

58. The age (a) of a plant is always expressed in years, and needs no definition except to say that it is usually reckoned from the date the plant or machine is a completed structure, installed and ready for service.

59. Present condition (p) is the ratio of wearing value less accrued depreciation, to wearing value. This can be expressed as

$$p = \frac{W - A}{W} = 1 - \frac{A}{W} \qquad (14)$$

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60. The annual depreciation charge (d) is the ratio of the number of dollars which must be set aside every year and placed in the depreciation reserve, to the original cost or investment; it is usually expressed as a percentage. The yearly (or monthly) accretions to the **depreciation reserve** are calculated in such manner as to produce, at the end of the life expectancy, a total fund equal to the wearing value. The annual sum (D), in dollars, charged to expense and credited to the depreciation reserve, can then be expressed by $D = dI$.

61. Segregation of plant into classes, for the purpose of computing the annual depreciation charge, is very essential for the reason that different kinds and types of plant have different life expectancies, and therefore depreciate at different rates. After the segregation process is completed and the annual depreciation is determined for each class or type, the sum of the annual charges for all the classes, in dollars, will give the total charge in dollars; the latter sum divided by the original cost or physical value of the whole plant will give the **composite depreciation charge** for the physical property as a whole.

62. Theories of depreciation.* There is no agreement at present concerning the question as to how, or in what manner, depreciation accrues from year to year during the life period. The discussion centres for the most part, in this country, around two well-known theories, one known as the straight-line method and the other as the sinking-fund method. There is also the method of diminishing values or reducing balances, and the annuity method. The first two methods are presented briefly in the following paragraphs.

63. The straight-line method is based on the assumption that depreciation accrues according to a straight-line law, in the simple ratio of age to life, as shown in Fig. 2. The formulas expressing the several relationships among the foregoing quantities or values (Par. **50** to **60**) are as follows:

$$\left.\begin{array}{lll} d = \dfrac{W}{lI} \text{ (per cent.)}; & A = adI & \text{(dollars)} \\ p = 1 - \dfrac{a}{l} = 1 - \dfrac{A}{W} \text{ (per cent.)}; & P = I(1-ad) & \text{(dollars)} \end{array}\right\} \quad (12)$$

The values of W and I are expressed in dollars and a and l in years. This method, as ordinarily applied, depends in no way upon the amount or rate of interest earned by the depreciation reserves, pending their use for renewals. The straight-line method of computing depreciation is in wide use and has received the approval of several Public Utility Commissions.

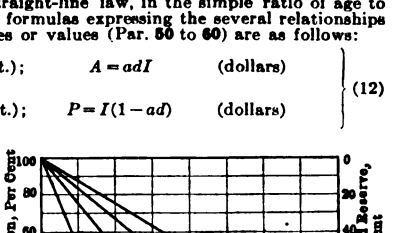


FIG. 2.—Depreciation diagram; straight-line theory.

64. The sinking-fund method is based on the assumption that depreciation accrues according to the law which expresses the accumulation of a sinking fund at compound interest (Par. **25**), as shown in Fig. 3. The formulas for use in this case are as follows:

$$\left.\begin{array}{ll} d = \dfrac{W}{I}\left[\dfrac{r}{(1+r)^l - 1}\right] & \text{(per cent.)} \\ p = \dfrac{(1+r)^l - (1+r)^a}{(1+r)^l - 1} & \text{(per cent.)} \\ A = W(1-p) & \text{(dollars)} \\ P = I - A = pW - R + S & \text{(dollars)} \end{array}\right\} \quad (13)$$

* Erickson, H. "Depreciation;" address before Central Water Works Association, Detroit, Mich., Sept. 25, 1912. Also see Bibliography, Par. **88**.

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The values of W and I are expressed in dollars, a and l in years, and r the annual rate of interest on the fund, decimally expressed. This method requires that the depreciation reserves be left undisturbed for the entire period of life expectancy, in order that the full amount or sum required to extinguish the wearing value may be realized; otherwise the sums received as interest will be impaired. The sinking-fund method has been employed by the Railroad Commission of Wisconsin: also see Floy, H., "Valuation of Public Utility Properties;" New York, 1912; Chap. VIII.

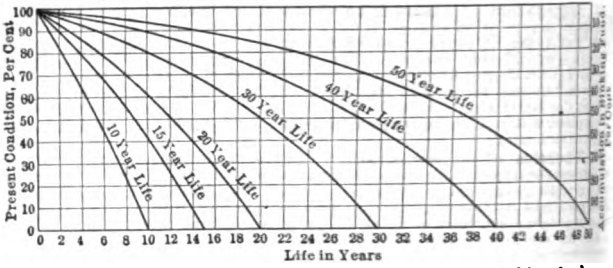


FIG. 3.—Depreciation curves; based on 5 per cent. sinking fund.

65. The method of reducing balances is rarely used in this country. It consists briefly in reducing the book value or worth of the plant each year by a fixed percentage. If this figure, for instance, is 10 per cent., the value at the commencement of the second year will be 90 per cent.; the third year, 81 per cent.; the fourth year, 72.9 per cent., etc. This method is interesting theoretically, but is not regarded as very practical.

66. Reserves for accrued depreciation. Expert opinions differ as to whether it is necessary to lay aside depreciation reserves for future use. In the case of a new property, just starting operations, there is no doubt that it is very essential to lay aside something for accruing depreciation, unless low finances make it absolutely impossible; unquestionably the time will arrive, at some future date, when replacements in this plant become necessary and the current revenues will be inadequate to meet the outlay, so that the wisdom of setting up a reserve is almost self-evident. The case just cited represents one extreme, in the range of possible or probable cases; the next illustration will be at the opposite extreme. Conceive a very large property, highly diversified as to different kinds and types of plant or equipment, and built up by piecemeal growth extending over a very long series of years; in this case the renewals from year to year probably will not vary to any great extent in number and cost, but perhaps increase slightly from year to year, on the whole, as the property increases in total bulk or size. There are many properties which are intermediate between these two extremes, and a reserve for accrued depreciation is therefore a very wise, if not a necessary provision; at the same time, this is not the universally accepted view.

From another standpoint, however, there is a very strong reason for creating depreciation reserves. Quite aside from the question as to whether a reserve is necessary in order to distribute the cost of renewals uniformly from year to year in the expenses of operation, it is unquestionably true that plants of practically every kind depreciate with age; that is to say, depreciation is always going on, beyond any power to prevent it. This being so, it becomes evident that the present worth of almost every kind of plant commences to decrease from the first day it enters service; therefore it is essential, from the standpoint of the stockholder or investor, to protect the original investment by creating a reserve to offset the accrued depreciation. If the depreciation which accrues annually is offset by charging an equal sum to expenses and crediting it to the reserve, each year, and if the cost of renewals as they occur is charged to the reserve, the whole matter of protecting the investment will take care of itself, in theory. In other words, under this plan, the sum of the present worth of the property plus the total reserve on hand, at any date, will always equal the original investment; this will be

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rue, whether the property grows rapidly, or slowly, and without regard to he size of the expenditures for renewals, provided only that the life expect- ncy of each increment or fragment of the property is realized with substantial ccuracy.

67. Investment of depreciation reserves. The proper disposition of lepreciation reserves, pending their use for the purpose originally intended, s a subject which has received much discussion without evolving any hard- nd-fast rule that meets with general approval. If the funds are not in- ested in some form of security, or in a business enterprise, they can hardly lraw a rate of interest in excess of the usual rates on time deposits, or say 3 per cent. per annum. If invested in conservative bonds, the rate may be as high as 5 per cent. If the property is one which earns more than 5 per ent., there will be some advantage in investing the depreciation reserve, r some portion of it, in extensions of the plant. The last plan also possesses he advantage of reducing the requirements for fresh capital in extending the usiness; indeed, in some cases it has become the policy to invest the whole lepreciation reserve in this manner.

When the depreciation reserve is set up on the basis that the total reserve hould always equal the accrued depreciation on the entire property, and the ntire reserve is invested in the property, there is one consequence which it s important not to overlook; namely, the present worth of the property will lways be equal, in theory, to the total investment in it by the stockholders r owners, assuming that the property is free of debt of any kind. The ropriety of investing the whole depreciation reserve in this manner is robably open to some question: in new plants just commencing operations, his procedure may possibly lead to financial embarrassment some years ater, when extensive renewals become necessary during some particular ear, and the necessary cash is not available except through the sale of new ecurities; in properties, however, of a highly diversified character as to ypes and kinds of plant, built up by piecemeal growth through a long series f years, the funds required for renewals during any particular year are not ikely to exceed the total sum set aside that year for accrued depreciation, nd therefore this plan is not very likely to lead to difficulties in such cases. Between these extremes, nevertheless, there are many intermediate situations, nd the ruling local conditions in each instance must largely determine the est course to pursue.

In the case of public utilities, or quasi-public corporations, the depreciation reserve is virtually a trust fund created by public contribution through he assessments or charges for service, and the income from the fund is roperly returnable to the fund and belongs thereto; but whether this in- ome is treated as a credit against current charges (expense) for accrued lepreciation, or whether it is treated as part of the total corporate income, nakes no difference in fixing the amount of the reasonable return on the nvestment.

Those who are particularly interested in this question should read the iterature which is to be found in the transactions of engineering societies, he technical press, the literature of accountancy and the authorities cited n the Bibliography, Par. 88.

68. Amortization is a term used in finance and accounting in the sense f extinguishment; for example, to amortize a debt by means of a sinking und (Par. 26), or to amortize the principal of an issue of bonds, or an indebt- dness represented by an issue of notes. The term should not be confused with depreciation. It can be correctly said, however, that the annual sums et aside for depreciation, and placed in a reserve fund, are for the purpose f amortizing the wearing value. Amortization means merely the extin- uishment of a parcel of value or money equivalent, by means of periodical harges spread over a period of time.

69. Depreciation accounting is too extended a subject to explain riefly. In general, the periodical sums necessary to cover depreciation are harged to operating expenses and concurrently credited to the reserve for ccrued depreciation. When plant is displaced, its original cost is credited o the fixed capital account and charged to the reserve; the reserve is also harged with the cost of removal and credited with the salvage, the latter eing concurrently charged to supplies. The new plant, which displaces the ld, is charged to the fixed capital account, under the appropriate sub- ccounts. Some authorities hold that accrued depreciation should be

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deducted from the plant investment, and the reserve for accrued depreciation carried as an asset; others hold that no deduction should be made, but that the reserve should be carried as a liability. The accounting rules of the Interstate Commerce Commission, and those of the State Public Service Commissions should be consulted by those who wish for more information as well as the text-book authorities; also see files of the *Journal of Accountancy*, for articles on depreciation and its treatment in accounting.

70. Appreciation may be defined as an increase in worth or exchange value; the converse of depreciation. In the physical sense, most kinds of property depreciate; but in the sense of market value, when regulated by the law of supply and demand, many kinds of property may appreciate. A familiar example of appreciation is found in the case of land, in a fertile or productive country of increasing population. The market value of land which is useful for business purposes often rises very rapidly.

SOCIAL-ECONOMIC INVESTIGATIONS

71. General. Lack of space forbids any extensive treatment of this subject, or more than a few references to its fundamental features. It forms the essential connecting link between engineering in the purely technical sense, and the social service rendered by engineering projects designed to satisfy public needs. Thus it occupies a position of the highest importance in every type of public utility engineering, and typifies the close relation of engineering, as a whole, to the social welfare.

72. Traffic analysis and considerations having to do with the handling of traffic, and the determination of traffic loads and delays, form an essential part of public utility and transportation engineering. Traffic questions are of prime importance in all forms of transportation and communication. In each type of case, the unit of traffic is different; it may be a passenger, or a unit of bulk or weight, or a message. But in every case the traffic itself may be defined as the flow of these units past a given point. The minute-to-minute or hour-to-hour variations in the flow constitute the traffic load curve, which is usually extended to further limits in order to reveal the day-to-day, week-to-week and month-to-month variations throughout a period of a year. Other types of curves show the delays to the traffic before it moves, and indicate the quality of the service in this particular.

Traffic data are fundamental, of course, in determining the required schedule of traffic vehicles, or the facilities needed to accommodate the traffic at any period. The volume of traffic, the quality of service and the net income on the investment are so intimately related that they cannot be independently considered in any successfully managed transportation or communication enterprise. For example, see a paper by the author, entitled, "Toll Telephone Traffic," *Proc.* A. I. E. E., June, 1914.

73. Statistics of demand and consumption are to electric, gas and water utilities what traffic analysis is to common carriers (transportation and communication). This analogy, while true in the broad sense, is somewhat imperfect as to detail. In the case of utilities, the statistics of demand and consumption relate wholly to the quantity of service, whereas the quality of the service depends upon both the quality of the delivered commodity and the continuity and uniformity of its supply. In other words, transportation and communication partake wholly of the nature of a service, whereas a utility furnishes both commodity and service. It is hardly necessary to dwell upon the importance of preserving continuous statistics of demand and consumption, from the standpoint of the financial results to the utility, because it is so evident. Electric central station statistics are given more elaborate consideration in another portion of this Section, see Par. 89 to 137.

74. Probable future development of the business of a public utility or a common carrier concerns itself with projecting or extrapolating the past and present experience into the future, for the purpose of forming a guide in shaping present policies of management. Investigations made for this purpose are sometimes termed development studies. The desired end in all such investigations is to forecast the probable future demand and consumption. The methods employed are sometimes elaborate, and lack of space forbids any attempt to go into details here. Passing reference will be made, however, to the usefulness of the law of probability in making investigations of this general character.

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75. Application of the law of probability. Experience shows that mand and consumption fluctuate to some extent, under similar conditions to time, locality, weather, etc., even when the periods compared are parated by no more than a day or a week intervening. Given a sufficient mber of observations on demand or consumption, taken under precisely milar conditions but on successive occasions, it becomes quite evident at the mathematical law of probability may be useful in computing the ost probable demand or consumption, and also in computing the probability at the demand or consumption will deviate by a specified amount from the ost probable value. The theory of probability constitutes the entire founda- on for the discussion of precision of measurements (Sec. 3), and has been plied in a number of other connections in engineering, among them being e analysis of telephone traffic. It also forms the whole basis, of course, every form of insurance.

VALUATION AND RATE MAKING

76. General. Valuation and rate making have become so important at at least five important and authoritative works dealing with this field ve been published since 1911. Only the barest outlines of the subject can given here, with references in the succeeding paragraphs and the Bibliogra- y to some of the principal authorities. Central-station valuation and rate king are treated at some length in Par. **128 to 158**, which should also be nsulted for a more detailed exposition of the fundamentals of the subject.

77. Standards of value by which to measure the fair value of a public ility have been the subject of extended discussion and litigation, without tablishing up to this time any well-defined conclusions except of the broadest aracter. Although the matter is still in its formative phases, the general inciple that investors in public utility enterprises are entitled to fair and asonable treatment at the hands of the public is well recognized. An cellent discussion of the present status of the matter will be found in . R. H. Whitten's "Valuation of Public Service Corporations," Supple- nt, 1914, Chap. II.

The courts have held that original cost, estimated present reproduction st, and outstanding securities issued against the property, are all com- tent evidence on the question of value; but the conclusion in every case ust be tempered by a consideration of all the facts and circumstances. his is very well expressed by the decision in the Minnesota Rate Cases 30 U. S. 352, 33 Sup. Ct. 729, June 9, 1913), "It is not a matter of formulas, t there must be a reasonable judgment having its basis in a proper consid- ation of all relevant facts."

78. Valuations under the cost-of-reproduction theory resolve emselves into two main questions: (1) What is the value of the tangible operty; (2) what is the value of the intangible property?

79. Tangible property consists of physical plant, such as right-of-way, nd, buildings, machinery, distribution system, meters, etc., organization d engineering expense, interest and taxes during construction; supplies d materials on hand, and working capital.

80. Intangible property consists of franchises, licenses, rights, contracts, od will and going value. The modern rule is to allow nothing for **fran- ise value** unless something was or is actually paid for it, or unless some lue for it has been capitalized in the past with public approval. Under nopoly, **good will** has been held to have no value for rate-making pur- ses. **Going value**, or going-concern value, has been extensively dis- ssed by engineers and commissions, but no recognised or authoritative e is yet in existence; an excellent summary of the theories of going value, d the tendencies of courts and commissions with respect thereto, is con- ned in Dr. Whitten's two volumes on "Regulation of Public Service rporations." See also Par. **156**.

81. Valuation of tangible property under the cost-of-reproduction sory involves two separate steps or procedures: (1) The preparations of **inventory** of the property; (2) the determination of **unit costs** and their plication to the quantities in the inventory, for the purpose of computing total reproduction cost-value, new or undepreciated. The unit costs uld be those, if possible, determined from the actual current construction ts shown by the corporate books, unless known to be objectionable for

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some good and sufficient reason, and therefore unreasonable for the purpose in hand. Unit costs which are unusually high or low by reason of exceptional prevailing prices for labor or materials should be avoided; for this reason average costs covering a period of several years past are sometimes employed.

83. Deduction of accrued depreciation, or cost new less depreciation is the generally accepted rule in preparing valuations. This has no immediate relation to the question whether a reasonable return will be permitted on the cost new, or the same less accrued depreciation; the proper or reasonable course in connection with the latter question will develop in the subsequent consideration of the merits of each case.

83. A reasonable return on the legitimate investment in property used and useful in the public service, considering the risk involved and the usual return on other investments involving similar degrees of risk, must in the long run be the guiding rule in fixing rates. If less than a fair return, as determined by this rule, is allowed in fixing rates, the securities of public utility enterprises cannot compete successfully in the investment market with other classes of investment and money will not be forthcoming for the extensions of such properties. On the other hand, if more than a fair return is allowed, the price of service to the public or the consumers will be unjustly high.

84. Theories of rate making. There are two fundamental theories of rate making, known respectively as the value-of-service theory and the cost-of-service theory. There has been much controversy between the advocates of these theories, the literature of which is very extensive. Since the whole subject is yet in the formative stage, it seems unwise to attempt more than a brief statement of each theory, in the two succeeding paragraphs.

85. The cost-of-service theory is based on the declaration of principle that every rate for service shall be equal, no more or less, to the cost of rendering the service. This definition comprehends such an interpretation of the term cost as to include a reasonable return (interest and profit) on the investment, in addition to all the other elements of cost or expense embraced in the term total annual charge (Par. **29**). The correctness of this theory in its broader aspects is very generally recognized, but there are numerous differences of opinion as to how far it can be applied in determining individual or class rates.

86. The value-of-service theory is the older theory, and comes down from the early days before public utility regulation had become an accepted institution. Under this theory the rates are regulated by what the traffic will bear. Competition was largely relied upon, before the days of regulation, to prevent the rates from becoming oppressive. It is not contended at the present time that the total profits of a public utility should be regulated by the value-of-service theory, but it is frequently contended, however, that this theory should be employed to temper the cost-of-service theory, in fixing individual or class rates.

87. Cost analysis for rate making involves the problem of determining the cost of each class of service. The difficulties in this process are numerous and it is invariably necessary to adopt certain assumptions as to how different kinds or elements of cost should be distributed or prorated among different classes of expense. Those who are seeking detailed information should consult the extensive literature on the subject, including the opinions and decisions of Public Utility Commissions; also see the treatment of central-station rate making, Par. **128** to **152.**

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CENTRAL STATION ECONOMICS

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CENTRAL-STATION FACTORS RELATING TO UTILIZATION OF INVESTMENT AND APPARATUS

89. Definition. In all engineering study of the economics of central stations for the supply of electric light and power for various purposes in a community, it is convenient and customary to use certain factors or unit values derived from other similar plants. The factors given here apply to electric generating transmission and distribution systems only and do not include other utilities such as electric railways, water works, gas works, ice plants and steam heating systems sometimes operated in connection with electric light and power plants and included in their reports.

90. Cost of plant per kw. of yearly maximum load. Since the cost of a plant depends so much upon the maximum load it must carry, this is an important factor as showing the amount of money actually invested to create a plant sufficient to carry a given maximum load. This cost usually varies between $200 and $500 per kw. based on 1913 prices and $300 to $800 based on 1920 prices. The average is probably somewhere between $250 and $300 per kw. based on 1913 prices and $375 to $500 based on 1920 prices. Of this 50 to 75 per cent. is usually in the distribution systems leaving 25 to 50 per cent. for the power plant. The cost of the distribution system part will be highest with underground distribution or where the consumers are scattered, and will be the least with overhead construction or in those localities where the density of consumption per mile of distribution mains is greatest. The cost of steam power plants is from $55 per kw. up to $150 based on 1913 prices and $75 to $250 based on 1920 prices. The lower figure is for the largest steam-turbine stations in locations where land is cheap and there are no expensive preparations of the site. The higher figure is for reciprocating-engine plants on expensive land, with all refinements, so situated that the labor cost of construction is high. If a plant has a very large reserve amount of apparatus in excess of that required to carry the maximum load of the year, this first cost per kw. of peak load will, of course, be higher than if there is little or no reserve.

91. Effect of transmission networks. Where, in addition to the generating and distributing plants there are transmission lines or networks the cost per kw. of yearly maximum is usually much increased, this cost increase being justified usually by low operating costs of the large generating plants feeding the network. Transmission lines cost from $500 per mile up, on a 1913 price basis and $800 up on a 1920 price basis.

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92. Gross annual earnings per kw. of yearly maximum load. These usually are between the limits of $60 and $140. They are most frequently between $80 and $100. This factor indicates whether the gross earnings are high or low for a given maximum load, and consequently whether the plant is selling its output to its best financial advantage. This factor is likely to be lowest when the annual load factor is lowest, hence the importance of improving the load factor.

93. Gross yearly earnings per kw. of maximum plant capacity. This factor is similar to the previous one except that it depends on plant capacity rather than the actual maximum load.

94. Gross yearly earnings per $100 cost of plant. This factor varies between $17 and $56. Assuming the plants under consideration to have been well managed and developed for a number of years, the lowest values will be found in some of the large plants where the operating expenses are correspondingly low but the investment is high on account of the expensive distribution system construction necessary to serve large areas. A low factor for this value may also be caused by overbuilding a plant for the territory it is to serve. The highest values are usually found in small and medium sized plants in new territory where the growth has been rapid, the construction inexpensive and the rates high. The operating expenses may be correspondingly high but this is not always the case.

95. Operating expenses in per cent. of gross earnings. Under operating expenses are here included all expenses except depreciation, interest, dividends and new construction chargeable to plant or capital account. Operating expenses of central stations operated with water power or, occasionally, with very economically operated steam-turbine plants may be as low as 45 per cent. Good practice usually ranges between 50 and 65 per cent.

96. Connected load per kw. of maximum station load. This is a combination of the demand and diversity factors. These factors (treated in Par. **106** to **115**) are chiefly of practical importance in making rates as they show the maximum demand made upon the station and consequently the relative amount of investment required by different classes of business. The total connected load per kw. of maximum station load, ranges from 1.2 to 3.6. On the majority of systems it will range between 2 and 3.

97. Kilowatts of transformer capacity per kw. of maximum station load in an alternating-current system, usually ranges from 1 to 2. It is lowest in systems where transformers are large and serve a large number of customers each. It is highest where the transformers are small and serve only a few customers each. In the majority of central stations if the transformer arrangement is well planned it is not necessary to have this factor more than 1.2 to 1.5 kw.

98. Kilowatts of maximum load per employee in all departments. In a large number of stations this ranges from 30 to 70. It seldom exceeds 100 excepting where a considerable output is sold wholesale. That the large stations do not show figures much higher than the small ones is probably due to the fact that the number of employees engaged on the distribution system and in looking after the wants of consumers and the perfection of the service is greater in proportion in the large than in the small systems.

99. Per cent. of kilowatt-hours lost and unaccounted for. This factor is the difference in per cent. between the kilowatt-hours sent out from the station bus bars and the kilowatt-hours registered on meters or otherwise accounted for. This loss includes loss in lines, loss in slow meters, core and copper losses in transformers and leakage through defective insulation. This seldom is less than 15 per cent., and it is most commonly between 20 and 30 per cent. It may be over 30 per cent. in alternating-current systems with a large number of small transformers and with a very small amount of energy sold per mile of line and per transformer. Obviously if a system were operated without selling any electrical energy, these losses would be 100 per cent.

100. Yearly load factor. This is the average load of the year divided by the maximum load and expressed in per cent. A purely lighting load in a small town will yield a yearly load factor under 20 per cent. In a large city it will be under 25 per cent. Addition of motor and heating appliance load has improved these low load factors from year to year during the history of the central station business. A load factor between 30 and 35 per cent.

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now common in the smaller plants having a moderate amount of power
isiness. A number of the largest power systems have over 50 per cent.
ad factor. A combination of lighting, power, and railway loads in a large
ty gives a load factor between 40 and 45 per cent. The load factor indi-
ites the percentage of time which the plant apparatus is lying idle, and it is
ie constant aim of central station companies to increase the load factor
id reduce the idle time, because interest must be paid on the investment
hether the apparatus is in use or not.

ENTRAL STATION FACTORS RELATING TO TERRITORY SERVED BY SYSTEM

101. Gross yearly revenue per capita of population. This factor
aries through a large range. Fourteen dollars per capita may be considered
ear the maximum at the present writing. This factor is usually higher in
ie Western part of the United States than in the Eastern. Some engineers
i making preliminary estimates on the possibilities of future gross earnings,
lopt a step-by-step schedule which increases from East to West. Gross
arnings of $9 to $10 per capita may now be considered reasonably attainable
nder ordinary conditions in most towns on the western side of the Mississ-
ppi Valley.

102. Cost of plant per capita. This is a factor used by some engineers
) indicate whether an excessive amount of plant has been put in for the
opulation to be served. Aside from this it is evidently dependent upon the
ross earnings per capita and the degree to which the territory has been
eveloped for electric service. An investment of $40 per capita in an electric
lant might be justified if the gross earnings were $10 per capita. In prac-
ce we find this varying from $3 to $35 per capita, pre-war cost.

103. Watts maximum load per capita. This factor is also an indica-
on of the extent to which the territory has been developed. If excessive
i proportion to gross earnings per capita, it would indicate bad management.
t usually ranges from 30 to 100.

104. Population per consumer. This will range from 5 to an indefinite
gure. Of course 5 represents near saturation. Such a condition can only
e attained in a prosperous country or suburban town.

105. Gross revenue per consumer. This factor when taken in con-
ection with a knowledge of the territory served may help to indicate whether
he large manufacturing power business or the small residential business
as been neglected. This factor may vary between $18 and $159, but its
ost usual range is between $40 and $70.

106. Demand factor. This is the actual maximum demand divided by
he connected load, expressed in per cent. It may be applied to a system, a
roup of consumers or any individual consumer. It is useful in determining
he apparatus which must be provided and the rates which can be made for
erving any given class of business. These factors can be determined only by
ctual measurement for different classes of customers with maximum-demand
neters.

For example, suppose we find by inserting maximum-demand meters in
he services supplying a number of drug-stores that the total maximum
lemand made by these stores during a year is 75 per cent. of what it would
ave been had the total connected load been turned on by each consumer at
ome time during the year. We would then say that the demand factor of
hese drug-store consumers is 75 per cent. In figuring on the amount of
pparatus needed to serve other drug-stores we would multiply the connected
oad by the demand factor which would give the probable maximum demand.

Mr. E. W. Lloyd in a paper entitled "Compilation of Load Factors,"
efore the National Electric Light Association in 1909, gave the results of
he experience of the Commonwealth Edison Co. of Chicago with a large
umber of consumers equipped with maximum-demand meters. The de-
nand factors of some of the most important classes of small and medium
ighting consumers given by Mr. Lloyd are shown by the table in Par. 107,
vhere the classification is according to business, without regard to the size
f the installation. Some of the more important demand factors of power
onsumers taken from the same paper are also given in Par. 109, where the
lassification is by size of installation. The load and demand factors of a
umber of larger consumers using both power and light as given by Mr.
loyd appear in Par. 108.

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Some years ago all consumers in Chicago were served through maximum demand meters. This practice was later changed so that consumers having less than 1 kw. connected have their maximum demands estimated according to a table prepared by averaging the previous experience of the company with consumers of this class. A table in Par. 110 gives the demand factor used for estimating maximum-demand in Chicago for such small commercial and residence-lighting customers.

This paper by Mr. Lloyd gives curves showing that the demand factor of residence customers having more than 1 kw. in lamps connected, falls gradually from about 47 per cent. with 1.5 kw. connected load to about 15 per cent. with 4.5 kw. connected load. Small stores and offices are shown to have a demand factor of about 63 per cent., with 1.5 kw. connected load, which gradually falls to about 50 per cent. at 4.5 kw. connected load. The curve in both cases following a straight line from 1.5 to 4.5 kw.

The Wisconsin Railroad and Public Service Commission in rendering its decision in the case of the Madison Gas and Electric Company's rates in 1910 assumed demand factors as indicated by the table in Par. 111. These demand factors, in turn, were derived from figures obtained by tests in Madison, taking also into consideration demand factors compiled by companies using Wright demand meters, summarized in Par. 112.

107. Demand Factors and Load Factors of Small and Medium Lighting Customers in Chicago, Classified by Business

(E. W. Lloyd)

Kind of business	Load factor	Demand factor (ratio of maximum to connected load)
	Per cent.	Per cent.
Banks	16.1	66.8
Churches	12.4	56.0
Hotels	24.4	28.0
Houses	7.8	43.0
Offices (business)	9.2	64.2
Offices (professional)	6.7	64.0
Pool and billiards	17.4	64.5
Printers and engravers	14.7	59.0
Restaurants	23.4	52.3
Saloons	20.8	62.6
Shops (barber)	11.5	70.4
Shops (machine)	8.7	37.2
Shops (tailor)	8.4	59.3
Stables (livery)	22.2	52.3
Stores (book and stationery)	11.7	66.4
Stores (cigar)	16.8	64.7
Stores (dry goods)	8.2	76.5
Stores (drug)	19.3	78.8
Stores (furniture)	6.0	69.7
Stores (grocery)	10.3	73.0
Stores (hardware)	10.6	40.0
Stores (house furniture)	7.8	52.0
Stores (jewelry)	15.0	64.1
Stores (shoe)	9.8	66.5
Stores (clothing)	6.6	52.9
Small hotels and rooming houses	26.0	67.4
Laundries	10.3	67.5
Theatres	17.2	49.0
Warehouses	12.0	41.4
Wholesale houses	19.4	46.6
Manufacturers	9.5	53.5
Hospitals	12.5	42.3
Flats	6.9	54.1

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26. Demand and load factors of large Chicago consumers; combined power and light
(E. W. Lloyd)

Kind of business	Load factor 8,760-hr. year, per cent.	Demand factor (ratio of actual max. to connected load, per cent.)
Butter and creamery	20	60
Breweries	45	60
Brass and iron beds	20	60
Biscuit manufacturers	35	55
Boots and shoes	25	65
Brass manufacturing	28	50
Boiler shops	18	45
Can manufacturers	30	70
Candy manufacturers	18	45
Clothing manufacturers	15	55
Clubs (large)	40	85
Department stores (large)	30	55
Electrical manufacturing	25	55
Express companies	40	60
Electroplating	25	75
Engraving and printing	19	60
Fertilizer manufacturing	75	40
Furniture manufacturing	28	65
Foundries	15	75
Forge shops	30	49
Grain elevators	10	75
Glove manufacturing	25	55
Grocers (wholesale)	20	55
Hotels (small)	35	50
Hotels (large)	50	40
Ice-cream manufacturing	45	75
Jewelry manufacturing	18	50
Laundries	25	70
Machine shops	26	55
Newspapers	20	75
Packing houses	30	75
Paint, lead and ink manufacturers	23	45
Paper-box manufacturers	25	50
Plumbing and pipe fitting	26	55
Post offices	50	30
Power buildings	27	40
Refrigeration	50	90
Railroad depots	50	50
Pneumatic tube	50	90
Soap manufacturers	25	60
Seed cleaners	25	55
Screw manufacturers	30	75
Spice mills	20	55
Saw manufacturers	30	55
Structural steel	22	40
Sheet-metal manufacturers	18	70
Stone cutters	17	55
Twine mills	30	60
Theatres	16	60
Large restaurants	50	60
Small restaurants	30	70
Woolen mills	27	80
Wood-working	28	65
Textile mills	20	65

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109. Demand factors of Chicago power consumers; classified by size

H.p. installed	No. of consumers	Demand factors, per cent.
1 to 5	2,900	75.4
6 to 10	456	64.5
11 to 20	237	64.7
over 20	307	42.9

110. Demand factors used for computing rates of small Chicago lighting consumers; classified by size

Kilowatt connected load	Demand factors		Kilowatt connected load	Demand factors	
	Commercial (per cent.)	Residence (per cent.)		Commercial (per cent.)	Residence (per cent.)
0.25	100	100	0.65	82	61
0.30	100	89	0.70	81	61
0.35	95	86	0.75	80	57
0.40	91	83	0.80	79	57
0.45	89	74	0.85	78	55
0.50	87	73	0.90	78	55
0.55	85	67	0.95	77	53
0.60	83	67			

111. Demand factors assumed by Wisconsin Commission for fixing rates at Madison

	Per cent.
Residence lighting first 10 lamps	60.0
Residence lighting over 10 lamps or 500 watts	33.3
Stores and offices	70.0
Restaurants and saloons	70.0
Lodge and dance halls	70.0
Laundries	70.0
Depots	70.0
Theatres	70.0
Hall lamps	70.0
Factories	55.0
Livery stables	55.0
Churches	55.0
Hotels and clubs	55.0
Schools	55.0
County and federal building	55.0
University of Wisconsin	30.0
Sign and outline lighting	100.0
One motor under 10 h.p.	90.0
10 h.p. installation with more than one motor	80.0
Motor installations with more than 10 and less than 20 h.p.	70.0
Motor installations 20 to 50 h.p.	60.0
Motor installations 50 to 100 h.p.	55.0
Motor installations 100 h.p. or over	50.0

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112. Demand factors compiled by Wisconsin commission from companies using Wright demand meters

	Per cent.		Per cent.
Stores	40 to 100	Laundries	60 to 75
Offices	57 to 87	Livery stables	52 to 58
Saloons	62 to 92	Lodge and dance halls	68
Restaurants	52 to 62	Depots	75 to 95
Factories	53 to 56	Theatres	49 to 89
Churches	56 to 85	Shops	55
Hotels	28	Machine shops	37 to 54
Clubs	28	Blacksmith shops	66
Schools	37 to 52	County and federal building	33 to 31

113. Diversity factor is the ratio of the sum of the maximum power demands of the subdivisions of any system to the maximum demand of the whole system. For example, suppose two consumers each have a maximum demand of 50 kw. The sum of their maximum demands would therefore be 100 kw. Suppose, however, these maximum demands do not occur at the same time so that a maximum demand indicator connected to supply both services would indicate a maximum of only 75 kw. The diversity factor would then be 100 kw. divided by 75 kw. or 1.33. In other words, the sum of the maximum demands of these two consumers would be 1.33 times the actual demand on the feeder.

If the consumer's maximum demand is known and the diversity factor for that class of business is also known, the maximum effective demand of the consumer at a given point (such as transformers or power station) is determined by dividing the consumer's actual maximum demand by the diversity factor between the consumer and the point under consideration.

The diversity factor is a most important element in central station electric supply; in fact it is one of the economic foundation stones upon which the central station industry is built. But for the fact that the various combined maximum demands of various consumers do not coincide, greater plant capacity would be required to serve them and rates for service would necessarily be high, because of the higher investment required.

Thorough study of diversity factors can be made only where maximum-demand meters are used for each consumer. Mr. H. B. Gear, distribution engineer of the Chicago central-station system has reported the results of such investigations at various times as indicated in the Bibliography at the end of this section. The accompanying table gives a summary of Mr. Gear's figures on diversity factors for lighting and power loads (Par. 115).

114. Classification of diversity factor. In an electric light and power distribution system there is first a diversity factor between the individual consumers and the transformer serving a group of such consumers because the maximum demands of the individual consumers do not come at the same time. There is next a diversity factor between different transformers and their feeders for similar reasons. Going back another step there is a diversity factor between various feeders entering a power-house or substation and the bus bars and on large systems there is a diversity factor between various substations, and the power station bus bars.

In the case of very large consumers their **individual diversity factors,** with reference to the annual system peak load, must be considered.

Par. 115 gives the diversity factor for each step from the consumer to the generating station in the first four items, while the last four items give the diversity factors step by step from consumer to generator.

To combine the demand and diversity factors so as to determine the maximum demand on a transformer, feeder or station, as caused by a given connected load, multiply the connected load by the demand factor and divide this product by the diversity factor.

The yearly diversity factor between lighting and power load, and electric street and elevated railway loads in Chicago is reported by Mr. Samuel Insull as allowing a saving in generating equipment of 8.1 per cent. for the period of heavy winter load of 1911 and 1912, by combining their sources of power supply.

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115. Diversity Factors
(H. B. Gear)

	Residence light, per cent.	Commercial light, per cent.	General power, per cent.	Large users, per cent.
Between consumers	3.35	1.46	1.44	.....
Between transformers	1.3	1.3	1.35	1.15
Between feeders	1.15	1.15	1.15	1.15
Between sub-stations	1.1	1.1	1.1	1.1
Consumer to transformer	3.35	1.46	1.44	.....
Consumer to feeder	4.36	1.90	1.95	1.15
Consumer to sub-station	5.02	2.19	2.24	1.22
Consumer to generator	5.52	2.41	2.46	1.45

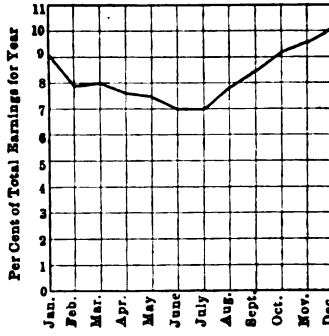


FIG. 4.—Variation of central station station earnings by months.

116. Variations in earnings from month to month by a central station are caused by increased demand for light during the winter season. In making estimates for the future it is frequently desirable to know about how these monthly variations run. The curve of Fig. 4 shows how the earnings vary from month to month as taken from a number of typical electric light and power systems of various sizes, with normal yearly growth

117. Yearly increase in output. The output and consequent generating capacity of the central stations of the United States as a whole is such as to double about every 5 years. This corresponds to an increase each year of about 15 per cent. over the year previous This being an average figure, due allowance must be made for local conditions in making estimates.

TYPICAL EARNINGS OF ELECTRIC LIGHT AND POWER COMPANIES

118. Finances. The following typical earnings of electric light and power companies in the United States are given as showing in a general way the relative values of capital account, gross income, operating expenses, depreciation, and net earnings available for interest and dividends, in electric light and power companies of several sizes, not operated in connection with any other public utility. While the figures given are typical of the sizes of plants named, considerable variation from them is found in practice. Some plants make a better showing than indicated in these typical cases, while others make a less favorable showing. The costs are pre-war, 1913, as 1920 conditions are too unsettled to permit typical examples.

119. The item of intangible value in the cases given represents whatever market value there may be in the plant over and above first cost of the physical property. It includes working capital, expenses of getting business started and worked up to a profitable basis, and any reasonable losses in connection therewith such as are allowed under the head of **going value** by the Wisconsin Commission. It may in some cases include some value based altogether on earning power. The intangible value of a property when determined for rate-making purposes by a public service commission is

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sually the amount of capital, over and above the cost of the physical plant, pon which the property will be permitted to pay common current interest r dividend rates.

120. The market value of such a property, if it has such value over nd above its physical value, is evidently its value to a prospective purchaser, nd the purchaser usually pays a price based on present and prospective arnings. What these earnings will be depends on the possibilities of the erritory served and if there be a rate regulating public service commission, t will also depend on the rate of return on the investment which will be llowed by the public service commission.

121. Central-station operation in connection with ice plant. As nany of the smaller light and power central stations are operated in connec- ion with ice plants the effect upon the first cost and earnings by adding such plant is given in two cases. The amount of ice manufactured per year, vhich determines the gross and net income, depends so much on the latitude n which the plant is located that considerable allowance must be made for his fact.

Ice plants, such as are mentioned in cases 4 and 5 (Par. **126** and **127**), night earn double the gross and about double the net earnings if located in he extreme southern part of the United States. The income from ice lepends also a great deal on whether it is sold wholesale or retail, or whether t simply supplies the population in its own town, or in addition ships to ther nearby points.

In comparing the typical cases given for the various sizes of plants, it will e seen that in general the gross earnings per $100 invested are larger in the uccessful small plants than in the large ones, but in the smaller plants the perating expenses are likely to be a larger percentage of the gross receipts. The larger plants can also obtain capital at a lower rate of interest.

The larger the plants the smaller the ratio of gross earnings to capital nvested. This is mainly due to the higher cost of transmission and distri- ution plants necessary to serve the larger territories supplied from the arger generating stations. In some cases it is also due to the higher cost f underground as compared to overhead distribution, and to a more sub- tantial character of construction.

122. Type of plant affecting various items. The typical examples iven are for steam-driven stations where the cost of fuel is near average. Higher fuel cost will, of course, raise the percentage of operating expenses, r, if more expensive machinery is put in to keep the fuel cost down, the apital account will be increased per kilowatt of peak load. Hydroelectric lants operating central-station lighting and power systems frequently nvolve higher first cost per kilowatt of peak load, and a consequent low ratio f gross earnings to capitalization. Such high first cost, of course, can nly be justified by the decreased operating expenses caused by fuel saved y water power operation.

123. Typical earnings of central stations. Case 1.

First cost of physical property		$37,500
Intangible value		12,500
Total capitalization		$50,000
Gross earnings (40 per cent. of capital)	$20,000	
Operating expenses (60 per cent. of gross)		$12,000
Depreciation at 6 per cent. on physical value		2,250
Net earnings for interest or dividends		5,750
	$20,000	$20,000

124. Typical earnings of central stations. Case 2.

First cost of physical property		$75,000
Intangible value		25,000
Total capitalization		$100,000
Gross earnings (33 per cent. of capital)	$33,000	
Operating expenses (58 per cent. of gross)		$19,140
Depreciation at 6 per cent. on physical value		4,500
Net earnings for interest or dividends		9,360
	$33,000	$33,000
Peak load of plant 300 kw.		
Gross income per kw. of peak		$110

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126. Typical earnings of central stations. Case 3.

First cost of physical property		$750,000
Intangible value		250,000
Total capitalization		$1,000,000
Gross earnings	$230,000	
Operating expenses (50 per cent. of gross)		$115,000
Depreciation at 6 per cent. on physical property		45,000
Net earnings for interest or dividends		70,000
	$230,000	$230,000

126. Typical earnings of central stations. Case 4.

Effect of 10-ton ice plant with electric plant like that in Case 1. Ice sold at wholesale. Latitude of central Mo. Compression plant.

Cost of ice plant		$8,000
Gross income from ice	$5,800	
Extra operating expenses for ice		$3,800
Depreciation at 6 per cent		340
Net for interest and dividends		1,660
	$5,800	$5,800

NOTE.—With sufficient cooling water available an absorption plant could be put in and would operate with much greater coal economy. Its first cost would be considerably higher.

127. Typical earnings of central stations. Case 5.

Effect of 15-ton ice plant operated with electric plant like that in Case 2. Ice sold at wholesale and retail. Latitude of southern Iowa.

First cost of ice plant		$12,000
Gross earnings, ice	$13,000	
Extra operating expenses for ice		$6,500
Depreciation at 6 per cent		780
Net for interest and depreciation		5,720
	$13,000	$13,000

PRINCIPLES OF RATE MAKING

128. Determining factors. The rates for service charged by a corporation giving central station electric light and power service must be such as to yield a gross revenue sufficient to pay operating expenses, interest, depreciation, and a fair profit on the enterprise. This constitutes the general problem of rate making. There are two general theories which have been used as a basis of rate making; these are given in Par. 129 and 130.

129. The value-of-service theory of rate making is that the rate of charge should be based on the value to the consumer of the service rendered. In railroad rate making this theory has been commonly referred to as "**Charging what the traffic will bear.**" Under this theory if a consumer is unable to obtain service except from some other very costly source, the rate to such a consumer could be made very high because of the absence of competition. Other consumers might be able to serve themselves or to get other services at such a low rate that their business could not be obtained except at a very close margin of profit for the central station, and to such a very low rate would be given. The value-of-service theory has undoubtedly had much to do with the making of central-station rates in the past, but present tendencies are to abandon this theory in favor of the cost-of-service theory, explained later. The value-of-service theory, or charging what the traffic will bear, if carried to an extreme logical conclusion might, in some cases, result in the central-station enterprise deriving an unreasonable profit from some of its customers and insufficient profit from others. In ordinary lines of trade and industry where there is free competition, the value of service theory is necessarily the basis of prices. An electric central station, however, is a public utility which is in the majority of cases a monopoly, at least as far as electric service in a given community is concerned. Because of the fact that it is a monopoly, both public sentiment and public service commissions generally are opposed to the principle of allowing a larger profit from one class of consumers than from another. For this reason the value-of-service theory is being abandoned. Its use in the past has not given

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rise to so great abuses in the rates of central station enterprises as might be at first supposed, because, although the central station frequently has a monopoly of electric service in a community, it has on every hand to meet the competition of other methods. Electric lighting comes into competition with gas and oil, and electric power with gas, steam and oil engines. However, as electric service becomes more and more of a necessity and less of the nature of a luxury, the tendency to regulate its rates in accordance with the cost of service to the producer rather than according to the value of service to the more or less helpless consumer, becomes stronger.

130. The cost-of-service theory of rate making is that all rates should be proportioned among the various consumers according to the cost of serving them. The term "Cost" in this case is assumed to include a reasonable profit. The cost-of-service theory is the one now generally used by the various public service commissions intrusted by law with the work of regulating and adjusting the rates of public service enterprises. The theory upon which the majority of such commissions are proceeding is that, on account of the monopolistic character of a public utility, its rates should be regulated in accordance with the cost of service including a fair return upon the capital invested in the public utility.

131. Definitions. The following definitions used in connection with electric central-station rates have been adopted by the Rate Research Committee of the National Electric Light Association. (Examples of all the forms of rates defined are given in Par. 151.)

Flat rate. The term "Flat rate" is applicable to any method of charge for electric service which is based on the consumer's installation of energy-consuming devices or on a fixed sum per consumer. Meters are not used.

Demand rate. The term "Demand rate" is applicable to any method of charge for electric service which is based on the maximum demand during a given period of time. The demand is expressed in such units as kilowatts or horse-power. Maximum-demand indicators or graphic meters are used.

Meter rate. The term "Meter rate" is applicable to any method of charge for electric service which is based on the amount used. This amount is expressed in units, as kilowatt-hours of electricity. Integrating meters or graphic meters are used.

Consumer's output rate. The term "Consumer's output rate" is applicable to any method of charge for electric service based on the consumer's output. The unit of the consumer's output may, for example, be a gallon of water pumped, a barrel of flour, or a ton of ice made.

Two-charge rate. The term "Two-charge rate" is applicable to any method of charge for electric service in which the price per unit of metered electric energy for each bill period is based upon both the actual or assumed quantity of electric energy consumed and the actual or assumed capacity or demand of the installation.

Three-charge rate. The term "Three-charge rate" is applicable to any method of charge for electric service in which the charge made to the consumer for each bill period consists of, (a) a sum based upon the quantity of electric energy consumed, (b) a sum based upon the actual or assumed capacity or demand of the installation, (c) a charge per consumer.

Straight line. The term "Straight line," as used in connection with and as applied to any method of charge, indicates that the price charged per unit is constant, i.e., does not vary on account of any increased or decreased number of units. The total sum to be charged is obtained by multiplying the total number of units by the price per unit.

Block. The term "Block," as used in connection with and as applied to any method of charge, indicates that a certain specified price per unit is charged for all or any part of a block of such units, and reduced prices per unit are charged for all or any part of succeeding blocks of the same or a different number of such units, each such reduced price per unit applying only to a particular block or portion thereof. The total sum to be charged is obtained by multiplying the number of units in the first block by the price per unit for that block and adding thereto the number of units in the second block times the price per unit for that block, and so on until the sum of the units falling within the different blocks equals the number of units to be charged for.

Step. The term "Step," as used in connection with and as applied to

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any method of charge, indicates that a certain specified price per unit is charged for all or any part of a specified number of units, with reductions in the price per unit based upon increases in the number of units according to a given schedule. The total sum to be charged is obtained by multiplying the total number of units by the price applying for this number of units, or by the primary price, and deducting the discount applying for this number of units.

132. The flat rate consisting usually of a fixed rate per month per lamp was the common rate in the early days of the electric-lighting industry. Its chief advantage is simplicity, as it requires no meter. It is still used generally for street-lighting contracts where a flat rate per lamp per year is charged. It is also used to a limited extent for other classes of business where the kilowatt-hours used can be definitely determined from the hours at which the supply is turned on and off or where the consumers connected load is too small to justify a meter. It is also used to some extent where there is no check upon the consumption of electricity but its use in this way can hardly come under the head of scientific rate making as it has no justification on economic grounds.

133. The straight-line meter rate, that is a rate under which a uniform price per kilowatt-hour is charged to all consumers, regardless of the quantity used or the conditionsof use, was at one time popular and is still used in many places but is now recognized as being utterly unfair because it takes no account of the great differences in the cost of serving different classes of consumers. The reason for these differences is explained later under the Two Charge or Hopkinson Rate (Par. **135**). In effect it makes some consumers pay the loss incurred in the supply of other consumers. Furthermore it has a very dwarfing effect upon the growth of the central-station business because of the impossibility of building up a large power business or securing large customers with such a uniform rate in vogue. Failure to secure such consumers means that the existing consumers must be charged higher rates than if a larger business were conducted by the central station.

134. The block meter rate and the step meter rate have been used to a considerable extent and represent an unsuccessful attempt to adjust properly the cost of service among different consumers by giving the consumers of a large number of kilowatt-hours per month a lower price per kilowatt-hour than the consumers of a smaller number of kilowatt-hours. These two rates are based upon the general law of commerce that it costs less to handle large or wholesale quantities of any commodity than to handle small retail quantities. However, these rates fail to take into account certain factors of the central-station supply business which affect the cost of service even more than quantity, as explained in Par. **135**. Their principle advantage is that they are easier to understand than some of the rates scientifically based on cost of service. They are used as a matter of expediency, legal necessity or ignorance. They cannot be classed as scientific rates under the cost-of-service theory.

135. Hopkinson two-charge rate. Dr. John Hopkinson in an address before the Junior Engineering Society in England, 1892, appears to have been the first to publish and make clear a thorough analysis of the various elements which should go to make up a rate based upon the cost of service. The Hopkinson method of estimating rates is now generally recognized by all authorities as correct where rates are to be based on cost of service. Various modifications and refinements of Hopkinson's original analysis have been introduced from time to time as mentioned later. The Hopkinson rate is one which would come under the head of a two-charge rate under the foregoing definitions.

The two-charge or Hopkinson rate is based on the facts that some of the costs of rendering service to a given customer are fixed annual expenses regardless of the kilowatt-hours actually consumed by such customer, while there are other costs which vary in accordance with the kilowatt-hours taken by the customer. As a simple example, take a consumer who makes a maximum demand of 1 kw. at the time of the maximum or peak load on the central-station plant. To serve this consumer a generating plant and distribution system must be provided, sufficient to supply that 1 kw. maximum to the consumer. To accomplish this end requires a certain investment upon which interest and a fair profit must be paid continually, and upon which depreciation is continually taking place. There are, also, other miscel-

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xed items, such as taxes and insurance, which are dependent entirely upon ıe size of the plant and which go on continually without regard to the kilo- ıtt-hours output of the plant. Such fixed charges are evidently propor- ional to the maximum demand of the customer without any regard to his ɔnsumption of electrical energy. If we find, for example, that the cost of ıe power station and distribution system per kw. of maximum load is 300, then that consumer who requires 1 kw. maximum should pay ɔntinuously, per month or per year, the interest, profit, taxes, depreciation, ısurance, etc., upon this $300 investment. This should be paid without ıgard to whether he uses a large or small amount of electrical energy in ilowatt-hours, because the investment has been made to serve him. In ddition to this he should pay a meter rate or charge per kilowatt-hour. 'his latter is to pay for the variable cost, principally fuel and labor, which aries according to the output of the station. As a matter of fact there re some labor and fuel costs which are dependent more upon the peak ıad of a station than upon the kilowatt-hours output and some authorities ɔuld include some of these costs in the fixed yearly or monthly maximum emand charge. However these are details aside from the main principle ıvolved. Plant conditions change with increasing load and it is more cus- ɔmary to count these fuel and labor items as variable in proportion to the ilowatt-hours output than as charges in proportion to the maximum de- ıand. We see then that the cost of serving a customer is divided into two istinct elements, viz., maximum demand, and kilowatt-hours, which hould be combined in making up a rate. The **demand charge** is sometimes alled a **readiness to serve charge.**

Following up our specific example; in the case of the customer making a naximum demand of 1 kw. upon the system at the time of maximum ystem load, the fixed or maximum demand charges against such a customer night then be found to be per year as follows:

Interest and profit on $300 per kilowatt plant and distribution **system** investment at 8 per cent.	$24.00
Taxes and insurance, 2 per cent. on $300	6.00
Depreciation at 6 per cent. on $300	18.00
Total fixed annual charges per kilowatt demand	$48.00

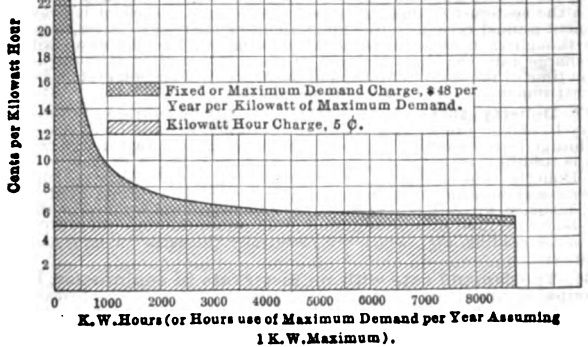


FIG. 5.—Typical form of cost curve for electrical energy supply.

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We will assume without itemising that the variable expenses such as labor, fuel, etc., amount to 5 cents per kw-hr. of output. That is to say, the variable expenses divided by the kilowatt-hours output equal 5 cents. We then have the two elements of the cost which in practice are either billed to the consumer as separate items or added together and converted into a charge per kw-hr. If we desire to determine the total cost of the two charges per kw-hr. it is determined by taking the sum of the maximum demand and kilowatt-hour charges and dividing this by the number of kilowatt-hours used.

The cost curve, Fig. 5, shows the sum of the maximum demand and kilowatt-hour charges under the foregoing assumptions of a demand charge of $48 per kilowatt maximum demand plus 5 cents per kw-hr, for the equivalent of various numbers of hours use per year of a 1-kw. maximum demand. It will be noted that the fixed or maximum-demand charges constitute a very large proportion of the total when the electrical energy is used but a short time per day or per year, while with electrical energy used continuously the maximum-demand portion is relatively small because it is divided among a large number of kilowatt-hours. This cost curve form is typical of all cost curves for electric supply.

In order to overcome the objections of many consumers, especially small consumers, to paying a fixed maximum-demand charge per month regardless of whether any electrical energy is used or not, it is common practice to accomplish practically the same ends by combining in some way, the maximum-demand and kilowatt-hour or output charges. The most common method of doing this is to charge a relatively high rate per kw-hr. until a given consumer has used enough electrical energy per month to pay for most of his maximum-demand charges plus the output charges, and after this amount or block of electrical energy has been used to make a much lower rate for additional blocks. This might be technically designated as a two-charge block rate.

136. The Wright demand rate is such a two-charge block rate. Mr. Arthur Wright put such a rate in force in Brighton, England, and described it in 1896 before the Borough Electrical Engineers' Convention. He invented a simple meter for measuring the consumer's maximum demand, which has been extensively used on Chicago consumers. This meter is not used, however, in the majority of cases where a two-charge block rate is in force.

An example of a common way of stating such a Wright demand or two-charge block rate is as follows: 14 cents per kw-hr. until the consumer has taken an amount of electrical energy equivalent to 30 hr. use per month of his maximum demand and 7 cents per kw-hr. for all electrical energy used in excess of aforesaid amount. Of course such a rate does not guarantee to the central station a minimum payment by the consumer per month sufficient to cover the fixed maximum-demand charges which the customer should justly pay but in practical effect it provides a sufficient annual revenue in the great majority of cases to cover these costs even though there is a loss on some consumers. In connection with any two-charge rate the determination of the consumer's maximum demand at the time of the maximum demand on the central station system becomes of great importance and this is discussed later.

137. Doherty three-charge rate. The Doherty rate, proposed by Henry L. Doherty in a paper before the National Electric Light Association at Chicago in 1900, differs from the Hopkinson rate or two-charge rate only by the addition of a third element commonly called a consumer charge. The Doherty rate is thus a three-charge rate. In Doherty's analysis of the rate-making problem he recognised that there is a certain fixed expense per consumer without regard to either the maximum demand or the kilowatt-hours required by such consumer. These are the expenses of bookkeeping, meter reading, etc., which are practically the same for large and small consumers.

138. The demand rate with no meter rate in conjunction has its principal application in sale of wholesale power from some hydroelectric plants where the investment and operating costs are fixed or constant, regardless of the number of kilowatt-hours used per year. The kilowatt-hour output in some cases is immaterial to the owner of the plant and the sum of the simultaneous demands of the different consumers at time of station maxi-

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mum load determines the amount of business which can be carried and the consequent gross revenue. A demand rate in effect is very similar to a flat rate. The only difference is that the consumer's maximum demand instead of being contracted for in advance is measured continuously and can be varied by the consumer from time to time without violation of contract.

139. Demand factor or the maximum demand made by the consumer is determined for rate-making purposes in various ways. The most common method with small consumers is to assume the consumer's demand factor or in other words to assume that the consumer's maximum demand is a certain percentage of the connected load. Such demand factors may be determined for different classes of consumers by test of a sufficient number of consumers with maximum demand meters and the results of such tests then taken as the basis of assumptions for all similar consumers. Such a method is of course somewhat inaccurate but it avoids the investment expense of a maximum demand meter for each consumer; which is an important item with small consumers. Demand factors as determined by various authorities for some classes of business are given in Par. **107** to **112**.

With large consumers it is frequently the practice to measure the maximum demand for a comparatively short period of time by means of an indicating instrument inserted at times of greatest load and assume that the maximum demand thereafter is the same as that measured.

140. Maximum-demand meters. In the Wright demand system of charging (Par. **136**) the maximum demand is determined by a **Wright demand meter** kept continuously in circuit alongside the kilowatt-hour meter. The Wright demand meter is an instrument for recording the maximum current which has passed and operates by the expansion and pouring over of a liquid by the heating effects of the current. It measures maximum amperes, not kilowatts.

A printing attachment on a recording watt-hour meter can be arranged to print at regular intervals the reading of the meter at that instant. The difference between two succeeding readings divided by the hours elapsed between readings gives the average demand in kilowatts between readings. By arranging the instrument to print at intervals of a few minutes, peak loads of very short duration can be measured. Such an instrument also shows the time at which the maximum demand is taken, thus showing whether at the time of the maximum load on the system or not; which in some cases is important.

Similar results are obtained by a make and break attachment on a watt-hour meter gear train connected to a separate clock instrument which charts the watt hours recorded within a given period, such as 15 minutes or 30 minutes.

A curve-drawing watt-meter which draws a curve of the load upon a roll of paper or circular chart is sometimes used for determining maximum demand where the meters can be looked after with sufficient frequency. It is usually considered practicable only in large installations.

141. The maximum demand in the case of residences is sometimes assumed to be proportional to the room area or to the number of certain kinds of rooms in a house. This is sometimes called the **Detroit system**, having been first used in America at Detroit. Under this system the residence consumer's maximum demand is assumed to be a certain number of watts for each different kind of room. Not all rooms are counted as only those rooms termed active are included and the number of watts per room is varied according to a schedule believed from experience to correspond to the average actual demand of such rooms. While such a method of figuring maximum demand would appear peculiar at first sight it is nevertheless probably as fair as an assumption that the maximum demand is a certain proportion of the connected load. Basing assumed maximum demand upon connected load in a residence has the serious drawback that it practically puts a penalty on the wiring of a house with a large number of closet lights and similar conveniences. These have but little influence upon the maximum demand but are nevertheless very convenient for the consumer and have much to do in persuading him to use electric light. Basing the maximum demand upon the active rooms in a house or upon the size of the house eliminates this unfairness and helps to cultivate the residence business.

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In England the **taxable (rateable) value** of a residence has been taken as a basis for the assumed demand in a few cases.

Where the maximum demand is assumed rather than measured it is customary in residence business under a two-charge block rate to include no electric heating devices, vacuum cleaners, washing-machine motors and the like in the connected apparatus counted as the basis of maximum demand. This is done upon the theory that such devices are not ordinarily used during the maximum or peak load of the station, or of the residence distribution system, so that there need be no investment or maximum-demand charge against them. The practical effect of such a policy is to give such heating devices a low rate because the ordinary residence consumer will consume enough electricity for lighting to exceed the primary or high-rate portion of his bill so that electricity used for heating and other household conveniences comes in on the low-rate portion of the bill.

142. Active-room-socket method of estimating maximum demand. (Cleveland method.) A further modification of the active-room plan of estimating demand, used at Cleveland, consists in counting the demand as being a certain number of watts per lamp socket connected in the active rooms. This is called the active-room-socket system.

143. Diversity of maximum demand, affecting investment charges. So far we have considered only the simple case of a consumer whose maximum demand comes at the same time as the peak load on the station or system. If the consumer's maximum demand is at a different time the problem is much more elaborate.

The maximum demands of different consumers do not all coincide as explained in Par. **113.** On account of the diversity between the demands of different consumers it must not be assumed that each consumer should be charged with the full station investment per kw. corresponding to the maximum kilowatt demand of such consumer. In order to determine definitely how much power-station investment should be charged against a given consumer, it is essential to know the diversity factor between the consumer and the power station or the maximum demand of such a consumer at the time of the maximum load upon the power station. As far as the power-station size and investment is concerned, the maximum demand of the consumer at times other than that of maximum power-station load is immaterial. Likewise, to determine the amount of feeder investment which should be charged against a consumer, it is essential to know the maximum demand of certain consumers at the time of the maximum load upon the particular feeder on which the consumer is located. The same process must be applied to mains and transformers.

A study of demand and diversity factors is therefore essential to scientific rate making in order that the proper relative amount of investment be charged against a given class of consumer. Demand and diversity factors are given in Par. **106 to 115.**

144. To determine the investment which should be charged against the service of a given consumer the method of applying demand and diversity factors is as follows: We will assume the case of a consumer with a connected load of 10 kw. We will also assume that the following demand and diversity factors have been found to apply to this class of consumers.

(a) Demand factor 80 per cent.
(b) Diversity factor consumers to transformers 1.43.
(c) Diversity factor transformers to feeders 1.25.
(d) Diversity factor feeders to power station bus bars 1.11.

The investment required for various parts of the plant to serve this consumer will then be as follows:

10 kw. in connected load × 80 per cent. demand factor = 8 kw. maximum demand at consumer's service, or 8 kw. meter investment.

8 kw. in consumer's demand ÷ 1.43 diversity factor, consumer to transformer = 5.6 kw. transformer investment.

5.6 kw. in transformers ÷ 1.25 diversity factor, transformers to feeders = 4.48 kw. feeder investment.

4.48 kw. feeders ÷ 1.11 diversity factor, feeders to power-station bus bars = 4.03 kw. power-station investment. It is of course necessary to such an analysis that the cost of the various parts of the system from the power station to the consumer be known, and the more exact such an analysis of cost the more equitable the rates that can be calculated there-

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rom. It is not however customary to attempt to charge each consumer with the exact feeder investment necessary to serve him. Some consumers are a considerable distance from the power station and others are near, and making an exact analysis would complicate matters to such an extent that t is customary to take the complete feeder and pole-line equipment reduced :o a cost per kw. of demand basis and to charge this investment equally among all consumers.

145. Off-peak rates, sometimes called limited rates are sometimes made for classes of business where the maximum demand of the consumer is imited to certain hours of the day so that all or a large portion, of the :onsumer's load is turned off during the hours of maximum central station oad. In this way the power station and distribution system investment which is installed to provide for the demands of ordinary consumers can be made to do double duty and the demand charge is considerably reduced. There is a difference of opinion among rate experts as to how much of the demand charge should be borne by the off-peak consumer in such cases. Some argue that, inasmuch as the station and meter capacity are already installed for serving the peak-load consumer, it is proper to eliminate a :onsiderable percentage of the demand charge for the off-peak consumer, because the power-station capacity service supplied to such a customer s in the nature of a by-product which would not otherwise be utilized. The general practice is to divide such charges between the peak and the off-peak consumers. However, in cases where it is necessary for competitive reasons to remove the demand charge of the off-peak consumers in so far as it applies to investment already made for peak consumers, and allow t to be borne altogether by the peak consumers, the by-product theory offers an excellent argument. Further, the taking on of such off-peak business, even though it bears but a small percentage of the maximum-demand charge, increases the net income of the company and assists in a more economical production, so that ultimately reduced rates can be instituted for all consumers. As a general policy the leaders of the central-station industry as well as public service commissions recognize fully that any rates which help to increase and build up the volume of central-station business help ultimately to reduce the cost of service to all consumers.

146. The practical deviations of rates from the cost-of-service theory are necessarily numerous. It is not feasible to determine the exact investment required to serve each consumer. Consumers must rather be taken by classes. Furthermore, the rate per kw-hr. to each consumer using electricity but a few hours per month based upon the cost of service, would be astonishingly high. If the rates charged on this business were based strictly on cost of service, there would be so much public protest that both central-station companies and rate-regulating commissions apparently have concluded that it is best to allow this class of business to be taken at a loss and let the losses be made up by other consumers, inasmuch as the gross revenue from such business is a small proportion of the whole.

147. Limited-demand flat rates are sometimes used for small residence lighting where it is desired to cut out the expense of meter investment, meter readings and bookkeeping. Such rates also appeal to a certain class of small consumers who wish to know definitely what their lighting bills will be per month without the uncertainty of a meter. One trouble with flat rates has been that consumers put in larger lamps or other devices than they contract to pay for. Under the limited-demand flat rate system the consumer is served through a limiting device of some sort which periodically interrupts the current and flickers the lamps whenever the contracted maximum demand is exceeded. The consumer is thus warned to turn off one or more lamps and prevented from using an excess demand over that contracted for.

The limited-demand flat rate has some of the disadvantages of all flat rates namely that consumers waste electrical energy by keeping lights on when not needed. Where such rates are in use, however, this tendency is somewhat restricted by making the consumer pay for lamp renewals, and if lamp renewals are sufficiently expensive there is some incentive to turn out lamps when not needed in order to save renewal costs. However such flat rates must always be made high enough to allow for considerable waste on the part of the consumer. The principal use for such a rate is in the supply of very small residences where the cost of bookkeeping, meter reading and

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meter maintenance would be a considerable percentage of the total monthly bill. A very common rate for this class of business in the United States for small residences is 1 cent per watt of demand per month. In calculating such rates it must be remembered that the diversity factor of this class of business as expressed in per cent. is higher than for ordinary residence business, because when service is supplied through a meter lamps are turned on and off as needed by the various consumers. The peaks of the various consumers thus do not coincide. Under the flat rate system there is likely to be but little diversity between consumers because the lights are left on continuously during the evening. The maximum demand of a group of such flat rate consumers per kw. of connected load will therefore be considerably more than for a group of consumers served through meters.

148. Rates for energy supplied for power purposes to electric motors are generally lower than those paid for electric lighting purposes. The scientific justification of such a policy is usually found in the fact that the maximum demand for electric power does not coincide with the maximum demand for electric light and the maximum demand for electric light is at the time of the maximum demand on the central station system. The motor load is, therefore, to a certain extent, an off-peak business even though it be not definitely stipulated in the contract that motors are not to be operated during the peak-load hours of the system.

149. Free lamp renewals. Some central-station companies give free lamp renewals of certain kinds of lamps and the cost of lamp renewals is included in the kilowatt-hour lighting rate.

150. A minimum bill or minimum charge per month is generally recognised as just by public service commissions and courts. These minimum charges are in the nature of a consumer charge to cover the cost of meter reading, meter and service maintenance and bookkeeping and to serve as a partial offset to the losses which inevitably occur under most rate schedules where the consumer uses electricity but a short time each month. Minimum charges are from $1.50 per month down for small consumers where such charges are in force. Some companies have no minimum charge, believing it is a deterrent to some would-be consumers, and the loss on some small consumers is assumed as a part of the expense of developing the business, popularising the service, and securing public good will.

151. Examples of rate schedules. The following rate schedules are given as specific examples of the rates defined and discussed in this section. The actual figures given are simply selected at random but they are within the range of ordinary practice and a number of the rates given are those actually in force in various cities.

Flat rate. One dollar per month for each 50-watt incandescent lamp or equivalent in commercial service. Fifty cents per month for each 50-watt incandescent lamp or equivalent in residence service.

Flat rate for street lighting. Seventy-five dollars per arc lamp (type of lamp being specified) per year, operating all-night every-night schedule, or about 4,000 hr.

Demand rate. Fifty dollars per kw. of maximum demand per year; the maximum demand being measured by a curve-drawing watt-hour meter.

Straight-line meter rate. Ten cents per kw-hr. for all electrical energy used. No discounts for quantity.

Consumers' output rate. Six cents per 1,000 gals. of water pumped. (In such a case the conditions of pumping are of course definitely known in advance of the contract. This is a form of rate sometimes used for waterworks pumping.)

Two-charge rate also known as the **Hopkinson rate.** Thirty-six dollars per year per kw. of maximum demand plus 6 cents per kw-hr. for electrical energy consumed.

Two-charge block meter rate with measured demand; also known as **Wright's demand rate.** A primary rate of 14 cents per kw-hr. for electricity used up to an amount equivalent to or less than the first 30 hr use per month of the maximum demand, and a secondary rate of 8 cents per kilowatt-hour for additional electrical energy.

Where the maximum demand is not actually measured the following is a typical form of expression of the two-charge block meter rate: Primary rate, 14 cents per kw-hr. for energy used up to an amount equivalent to or less

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than the first 30 hr. use per month of the active connected load. Secondary rate, 8 cents per kw-hr. for additional energy used. (In this case the active connected load is the assumed maximum demand.)

Where the active room plan is used as a basis of estimating maximum demand of residences, the following is an example of one method of estimating: multiply the number of rooms in the house by 0.04 kw., but do not count bathrooms, basements, cellars, porches, stairways, attics, store rooms, small halls, entrances, woodsheds, or barns.

Three-charge rate. Six dollars per year per consumer (as a consumer charge) plus $30 per year per kw. of maximum demand (as a demand charge sometimes called a readiness to serve charge) plus 6 cents per kw-hr. for electrical energy used.

Block meter rate. For the first 250 kw-hr. monthly consumption, 10 cents per kw-hr.; for the next 250 kw-hr. monthly consumption, 9 cents per kw-hr.; for the next 250 kw-hr. monthly consumption, 8 cents per kw-hr.

Step meter rate. For the first 250 kw-hr. of monthly consumption 12 cents per kw-hr.; for a monthly consumption between 250 and 500 kw-hr., 11 cents per kw-hr.; for a monthly consumption between 500 and 750 kw-hr., 10 cents per kw-hr. (Note that under the foregoing schedule a consumer of 249 kw-hr. per month would pay more than a consumer of 251, in actual dollars and cents. There is evident injustice in this and also in the fact that the discount is applied in sharp steps rather than gradually.)

152. Discounts for prompt payment are sometimes allowed and as the majority of consumers will take advantage of such discount the rates should be adjusted so that they will yield the owners of the property a fair profit after the discount is taken off. In order that a discount for prompt payment may be legally sustained it is necessary that it should not be a very large discount. About 10 per cent. is common. Discounts in excess of this are in danger of being set aside by courts or commissions as being unfair to the consumer who does not take advantage of the discount.

VALUATIONS FOR RATE-MAKING PURPOSES

153. Classification of purposes for which valuations are made. The laws of many states where public service or public utility commissions have been created for the purpose of public-utility regulation, provide for the valuation of public utility properties for purposes of establishing reasonable rates. The theory upon which these laws are based (although it is not always expressly so stated) is that of allowing the investor in public utility properties a fair and reasonable rate of return (interest and profit) upon his investment.

Valuations made for rate-making purposes may be very different from valuations made for other purposes. If a property is to be appraised or valued for the purposes of an ordinary business purchase, the fundamental question to be solved is the probable earning power of the property both present and prospective. In valuations for rate making, however, the earning power of the property should receive no consideration, because the earning power is dependent upon the very rates which it is proposed to regulate, and to value a property on its earnings would defeat the entire end in view.

154. The purpose of a valuation to be used in rate making, should be to determine as nearly as possible the actual fair investment in the property to the end that rates may be so adjusted that a fair annual return (interest and profit) will be made to the investor upon the amount invested in the property after all expenses are paid. If this end were kept constantly in view many of the disputes and discussions in connection with such valuations would be obviated.

If the actual cost of a public-utility property could always be obtained from the construction or property accounts, the problem would be simple. However, it is frequently the case that construction costs are not kept in such shape that they can be accepted unquestionably by the appraiser. It may also happen that part of the books and records of the enterprise is destroyed or unavailable. In any case the engineer making the valuation must be prepared by knowledge of other plants to check the accuracy of any figures submitted to him or even to value a plant entirely in accordance with costs of similar plants elsewhere if no figures whatever are available on the actual cost of the plant under consideration. The value of a public utility property is usually classified under two heads, tangible and intangible.

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155. The tangible physical property can be seen and appraised by an engineer familiar with the costs of similar plant and equipment as installed ready to run. As we are seeking for the actual first cost of such plant and equipment, the cost of building the plant at the time and in the manner in which it was actually built must be sought, rather than the cost of reproduction of such a plant at the present time. In this connection a reasonable allowance may be made for ever present minor mistakes in construction and the cost of their correction, unless such mistakes are such as to show a lack of ordinary good business judgment or management on the part of the constructor and investor. Depreciation should be deducted.

156. Intangible values are those not represented by visible, or tangible physical property. They are a prolific source of controversy. Keeping in mind the fundamental principle of allowing a fair interest and profit on actual cost of a property we see that under intangible value should be included all money put into the property at any stage of its development for whatever purpose, from whatever source, after deducting that coming under the following descriptions:

(A) Cost less depreciation of tangible property already listed.

(B) Interest, profits or dividends paid in the past in excess of a fair rate of return.

(C) Money invested as a result of extravagance, dishonesty, bad management or lack of ordinary reasonable business judgment.

Note that if these deductions are large enough to leave no intangible value the tangible property cost less depreciation becomes the fair value upon which a fair return should be paid. In such a case the owners would either have had the amount spent on intangibles, including an amount equal to the depreciation, returned to them in dividends or the intangible value including depreciation would have vanished through dishonesty or bad management.

Under the foregoing method of arriving at intangible value (termed **going value** by the Wisconsin Commission) the investors are permitted a return on money put into a plant to pay operating losses before getting it on a paying basis as well as money put into permanent plant, providing the money was honestly and carefully spent as before specified, and provided they have not already been reimbursed for such losses. Manifestly, to determine such intangible or going value, an investigation must be made, not only of present conditions but of the financial history of the enterprise.

Among items of intangible or going value which are fairly allowable are discounts on sale of bonds, notes and stock and all reasonable expenses of financing and promotion, and interest during construction. Sufficient working capital must be provided to pay running expenses pending the collection of income and a fair rate of annual return should be allowed upon such working capital as well as upon the capital permanently invested in plant and equipment.

After intangible or going value is determined it may either be figured in as a part of the capital upon which a fair interest and profit should be perpetually earned, or it may not be figured in as a part of the permanent investment and sufficient net earnings may be allowed the investors to amortize or wipe out such intangible or going value at the end of a period of years. Both methods are in vogue.

157. Treatment of depreciation. In such valuations a determination of the actual depreciation as well as a fair depreciation on properties of this class are of much importance for the following reasons. If the owners have been receiving dividends or interest in excess of a fair interest and profit and these excess dividends were taken out of funds which should have been put back into the plant to make up depreciation and maintain the property is an unimpaired condition which would represent full security for the capital invested, such excess dividends should be deducted from the valuation of the plant, because this amount of value has already been returned to the owners. Depreciation due to gross carelessness or neglect or mismanagement will not ordinarily be allowed, but a fair rate of depreciation should be allowed and set aside or spent in renewals and if the enterprise has not been able to earn enough to pay such fair depreciation plus a fair profit under reasonably good management any such deficit can be reasonably put in as a part of the intangible or going value of the plant. In other words depreciation is simply one of the expenses of the operation which should be recognized and provided for, even though part of it is not

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ayable until some time in the future (see Par. 42). If the earnings in he past have not been sufficient to pay all such expenses and a loss has re-ulted from operation, such losses should be included in intangible or going alue after making the proper deductions as stated.

State commissions in recent years have been allowing estimated charges or depreciation as a part of annual expenses to the amount of about 4 to 6 er cent. on the physical property valuation of the central station property aken as a whole.

158. The per cent. upon the investment which a public utility is llowed to earn as a fair and reasonable annual interest and profit upon its alue as taken for rate-making purposes is a matter for commissions and ourts to decide in accordance with the prevalent or market interest rate pon investments in similar securities. Public utility securitics must com-ete in the financial market with other securities or they will not be sold. hese are financial rather than engineering questions, but, since the engineer nust frequently deal with them in the course of his business, the following oints are given as presenting current practice.

Where part of the money to pay for the construction of a plant is raised y a bond issue, it is customary to sell the bonds at a discount below par, a art or all of which discount is taken by the bond broker as his commission or finding purchasers for the bonds. As the bonds must be redeemed at ar when they are due, the discount upon the bonds must be added to the otal annual interest paid on the bonds, in order to determine the actual nnual cost to the public utility for the use of the money. This is a point ometimes overlooked in figuring the fixed charges which a public utility nust carry. The principal question is to determine what rate of interest nd profit a public utility must pay after discounts or commission on sale f securities are included. It is not a question of theory but of market onditions.

Mr. Halford Erickson member of the Railroad and Public Service Com-nission of Wisconsin in a public address 1914 (see Bibliography) gives the ollowing figures as to rates actually paid by public utilities for money: en representative first mortgage bond issues covering electric-lighting and treet-railway plants, brought out in 1913 and bearing interest at 5 per cent. n par value, were placed on the market at prices at which they would yield he investor an income of from 5 to 6 per cent. The cost to the issuing ompany of obtaining this capital amounted to from 1 per cent. minimum o over 11 per cent. maximum for discount and about 3 per cent. for selling xpenses. The total average was about 6.2 per cent. During the same eriod 10 representative second mortgage bond issues covering gas, electric-ighting, and railway plants, bearing interest at 5 per cent., were offered t prices that would net investors an income of 5 to 6.2 per cent. On these ssues the discount varied from 1 to over 12 per cent. and the selling expense ood at about 3 per cent. The total cost to the companies for this financing anged from 5.2 to about 7 per cent., the average being about 6.4 per cent. welve note issues were offered to the public at prices which placed them pon a 6.2 per cent. income basis to the investors. When the discounts nd selling expenses were taken into account, the cost to the companies of he bonds thus obtained was found to be about 9.4 per cent. per annum. n this case the discounts ranged from less than 1 to about 2.34 per cent. he selling costs, however, were rather heavy since they appear to have anged from about 5 to over 8 per cent. Five preferred-stock issues were old on a basis whose average yield to the investor was about 7.3 per cent. ince the discounts varied from 3 to 12.5 per cent. and the selling expense lso had to be met, the cost to the companies was, of course, much greater han the price to the public. For about 40 plants in Wisconsin whose ap-raised value varied from about $20,000 to about $2,000,000 per plant, the onds, when discounts and selling expenses are included, were at that time elling at prices under which the cost of financing on the plant ranges from bout 5.5 to fully 6.5 per cent. per annum. In these cases the bonds cov-red from 50 per cent. to more than 85 per cent. of the values of the plants nd their business, while the net earnings of the plant did not amount to ss than twice as much as the interest on the bonds.

In 1920 public utility issues similar to those described by Mr. Erickson ould net the investor from 2 to 4 per cent. more and cost the utility com-any correspondingly more.

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